

Emissions of Greenhouse Gases in the United States 1999

October 2000

Energy Information Administration
Office of Integrated Analysis and Forecasting
U.S. Department of Energy
Washington, DC 20585

This publication is on the WEB at:
www.eia.doe.gov/oiaf/1605/ggrpt/index.html

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The authors would also like to express their gratitude to all the people who provided information or comments on this report, and particularly to David Costello and Elias Johnson of EIA's Office of Energy Markets and End Use, who provided weather-adjusted and related runs of the Short-Term Integrated Forecasting System (STIFS) model.

Preface

Title XVI, Section 1605(a) of the Energy Policy Act of 1992 (enacted October 24, 1992) provides:

Not later than one year after the date of the enactment of this Act, the Secretary, through the Energy Information Administration, shall develop, based on data available to, and obtained by, the Energy Information Administration, an inventory of the national aggregate emissions of each greenhouse gas for each calendar year of the baseline period of 1987 through 1990. The Administrator of the Energy Information Administration shall

annually update and analyze such inventory using available data. This subsection does not provide any new data collection authority.

The first report in this series, *Emissions of Greenhouse Gases 1985-1990*, was published in September 1993. This report—the eighth annual report, as required by law—presents the Energy Information Administration’s latest estimates of emissions for carbon dioxide, methane, nitrous oxide, and other greenhouse gases.

The estimates of greenhouse gas emissions contained in this report are based on energy consumption data from the Energy Information Administration’s (EIA’s) July 2000 *Monthly Energy Review*. Those estimates may differ from other EIA data series prepared after July 2000. Future revisions to the *Monthly Energy Review*, or other EIA data series, will be represented in the next annual report of *Emissions of Greenhouse Gases in the United States*.

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Executive Summary

Introduction

U.S. Anthropogenic Greenhouse Gas Emissions, 1990-1999

	Carbon Equivalent
Estimated 1999 Emissions (Million Metric Tons)	1,832.6
Change Compared to 1998 (Million Metric Tons)	14.4
Change from 1998 (Percent)	0.8%
Change Compared to 1990 (Million Metric Tons)	177.6
Change from 1990 (Percent)	10.7%
Average Annual Increase, 1990-1999 (Percent)	1.1%

Total U.S. emissions of greenhouse gases in 1999, estimated at 1,833 million metric tons carbon equivalent, were 0.8 percent higher than the estimated 1998 level of 1,818 million metric tons carbon equivalent. The increase was slightly lower than the 1.1-percent growth rate that has characterized total U.S. greenhouse gas emissions during the 1990s but significantly higher than the 0.1-percent growth between 1997 and 1998. By comparison, U.S. real gross domestic product (GDP) grew by 4.1 percent from 1998 to 1999. The relatively moderate increase in estimated greenhouse gas emissions in 1999

is attributable primarily to warmer-than-normal winter weather and to an increase in electricity generation from nuclear power plants.

Overall, 1999 U.S. greenhouse gas emissions were about 10.7 percent higher than 1990 emissions, which are estimated at 1,655 million metric tons carbon equivalent. The 1.1-percent average annual growth in U.S. greenhouse gas emissions from 1990 to 1999 compares with average growth rates of 1.0 percent for the U.S. population, 1.5 percent for energy consumption, 2.2 percent for electric power generation, and 3.1 percent for real GDP.

Table ES1 shows trends in emissions of the principal greenhouse gases, measured in million metric tons of gas. In Table ES2, the value shown for each gas is weighted by its global warming potential (GWP), which is a measure of “radiative forcing.” This concept, developed by the Intergovernmental Panel on Climate Change (IPCC), provides a comparative measure of the impacts of different greenhouse gases on global warming, with the effect of carbon dioxide being equal to one.¹

U.S. greenhouse gas emissions generally follow trends in U.S. energy consumption. In 1999, for example, some 82 percent of U.S. greenhouse gas emissions consisted of carbon dioxide released by the combustion of energy fuels—coal, petroleum, and natural gas (Figure ES1). In recent years, national energy consumption, like emissions, has grown relatively slowly, with year-to-year fluctuations in the growth rate of energy consumption largely caused by variations in weather patterns, business cycles, fuel use for electricity generation, and domestic and international energy markets.

Table ES1. Summary of Estimated U.S. Emissions of Greenhouse Gases, 1990-1999
(Million Metric Tons of Gas)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Carbon Dioxide	4,951.9	4,907.6	5,005.3	5,121.6	5,215.7	5,260.6	5,441.6	5,519.0	5,527.1	5,598.2
Methane	31.7	31.9	32.0	31.1	31.2	31.2	30.2	30.1	29.3	28.8
Nitrous Oxide	1.2	1.2	1.2	1.2	1.3	1.3	1.2	1.2	1.2	1.2
HFCs, PFCs, and SF ₆	*	*	*	*	*	*	*	*	*	*

*Less than 0.05 million metric tons of gas.

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999).

Source: Estimates presented in this report.

¹See “Units for Measuring Greenhouse Gases” on page 2, and Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

Table ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1990-1999
(Million Metric Tons Carbon Equivalent)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Carbon Dioxide	1,351	1,338	1,365	1,397	1,422	1,435	1,484	1,505	1,507	1,527
Methane	182	183	183	178	179	179	173	172	168	165
Nitrous Oxide	99	101	103	103	111	106	105	104	103	103
HFCs, PFCs, and SF ₆	24	22	24	24	25	29	33	35	40	38
Total	1,655	1,644	1,675	1,702	1,737	1,748	1,796	1,816	1,818	1,833

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999).

Sources: **Emissions:** Estimates presented in this report. **Global Warming Potentials:** Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

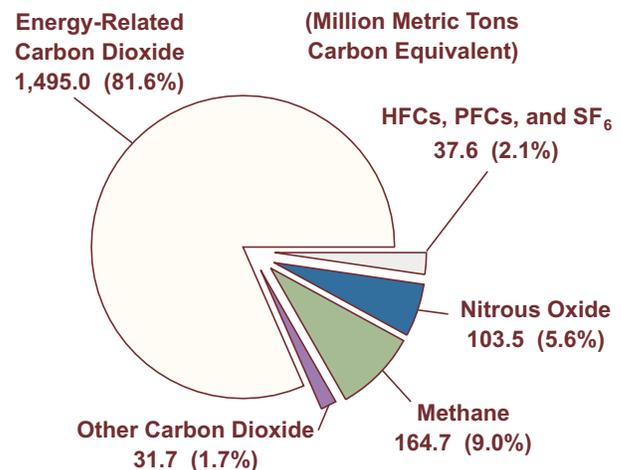
Other 1999 U.S. greenhouse gas emissions include carbon dioxide from non-combustion sources (2 percent of total U.S. greenhouse gas emissions), methane (9 percent), nitrous oxide (6 percent), and other gases (2 percent) (Figure ES1). Methane and nitrous oxide emissions are caused by the biological decomposition of various waste streams and fertilizers, fugitive emissions from chemical processes, fossil fuel production and combustion, and many smaller sources. The other gases include hydrofluorocarbons (HFCs), used primarily as refrigerants, perfluorocarbons (PFCs), released as fugitive emissions from aluminum smelting and also used in semiconductor manufacture, and sulfur hexafluoride (SF₆), used as an insulator in electrical transmission and distribution equipment and as a cover gas in magnesium production and processing.

The Kyoto Protocol, drafted in December 1997 under the auspices of the United Nations Framework Convention on Climate Change, raised the public profile of climate change issues in the United States in general, and of emissions estimates in particular. Although the Protocol has yet to be ratified by enough nations, including the United States, to “enter into force,” emissions inventories are the common yardstick by which success or failure in reducing emissions—an objective of the Protocol and the Framework Convention on Climate Change—would be measured. This report, required by Section 1605(a) of the Energy Policy Act of 1992, provides estimates of U.S. emissions of greenhouse gases, as well as information on the methods used to develop the estimates.

Carbon Dioxide

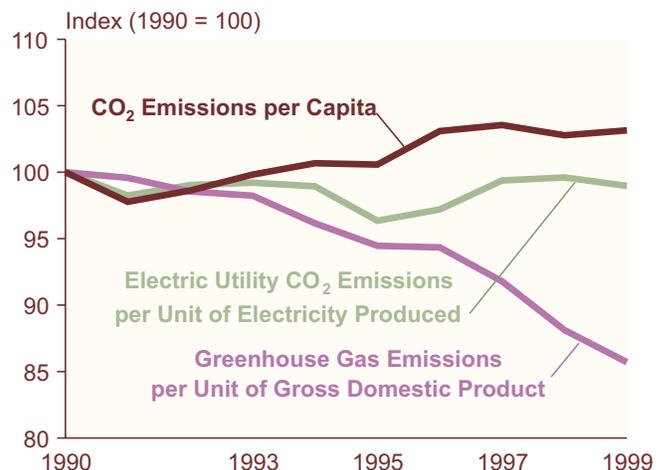
U.S. carbon dioxide emissions in 1999 are preliminarily estimated at 1,527 million metric tons carbon equivalent—1.3 percent higher than in 1998 and accounting for 83 percent of total U.S. greenhouse gas emissions. Figure ES2 illustrates some recent U.S. trends in carbon dioxide emissions and energy consumption. Carbon dioxide

Figure ES1. U.S. Greenhouse Gas Emissions by Gas, 1999



Source: EIA estimates presented in this report.

Figure ES2. Carbon Dioxide Emissions Intensity of U.S. Gross Domestic Product, Population, and Electricity Production, 1990-1999



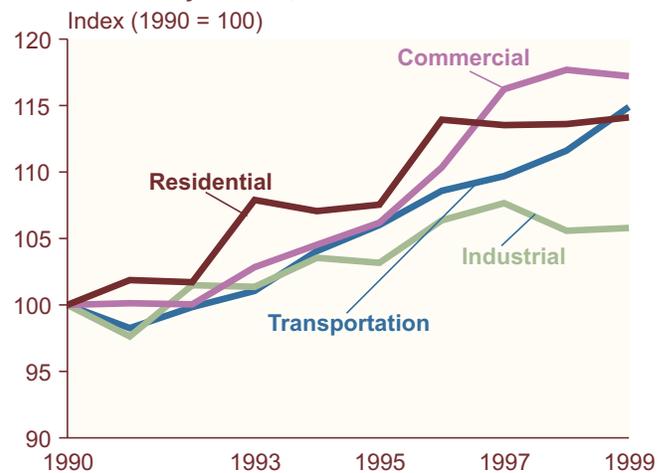
Sources: Estimates presented in this report.

emissions per dollar of GDP and carbon dioxide emissions per capita are approximate measures of the “carbon intensity” of energy use. Per capita carbon dioxide emissions declined in the early 1980s but rose in the 1990s at a relatively low rate of 0.3 percent per year. Carbon dioxide emissions per dollar of GDP have declined almost every year, averaging an annual 1.7-percent rate of decline during the 1990s. During the early 1990s, several unrelated factors—including improved nuclear power plant operating rates and relatively low natural gas prices leading to an expansion of natural-gas-fired electricity generation—combined to lower the carbon intensity of electric power generation (carbon dioxide emissions per unit of net generation).

Figure ES3 illustrates trends in carbon dioxide emissions by energy consumption sector. In general, emissions have increased in each of the four sectors since 1990. An exception to the general upward trend was 1990-1991, when economic recession and higher oil prices following the Iraqi invasion of Kuwait led to a 0.9-percent decrease in national carbon dioxide emissions in 1991. Average annual growth rates in carbon dioxide emissions by sector during the 1990s were 1.8 percent for the commercial sector, 1.6 percent for the transportation sector, and 1.5 percent for the residential sector, all higher than the 1.4-percent average for total U.S. carbon dioxide emissions during the decade. For the industrial sector, however, annual growth in carbon dioxide emissions averaged only 0.6 percent during the 1990s. Industrial sector carbon dioxide emissions, which are relatively sensitive to economic fluctuations, declined by 2.4 percent in 1991 during the economic recession and dipped again in 1998 in the wake of the Asian economic slowdown.

Carbon dioxide emissions from the U.S. electric power sector in 1999 are estimated at 614 million metric tons carbon equivalent—1.0 percent higher than the 1998 level. The 1999 increase is less than half the 1990-1999 average increase of 2.1 percent per year. Contributing to the relatively small increase in 1999 was an 8.1-percent increase in electricity generation from nuclear power plants relative to their 1998 output.² Electricity-related emissions in the residential sector were 1.2 percent lower than in 1998, and in the commercial sector they were 1.4 percent lower.³ Although summer cooling degree-days were 2.9 percent above normal in 1999, air conditioning usage was lower than in 1998, when cooling degree-days were 18.2 percent above normal.

Figure ES3. U.S. Carbon Dioxide Emissions by Sector, 1990-1999



Sources: Estimates presented in this report.

In addition to electricity-related emissions, direct use of energy fuels in the residential, commercial, industrial, and transportation sectors produces carbon dioxide emissions. In the residential and commercial sectors, consumption of winter heating fuels, particularly natural gas, was higher in 1999 than in 1998 as a result of winter weather that was 7.4 percent colder than in 1998.⁴ Carbon dioxide emissions from the direct combustion of fuels (primarily natural gas) increased by 3.9 percent in the residential sector and by 2.6 percent in the commercial sector. Overall, carbon dioxide emissions in the residential and commercial sectors, at a combined 534 million metric tons carbon equivalent and 35 percent of total emissions, grew by 0.1 percent in 1999.

Energy-related carbon dioxide emissions in the industrial sector in 1999 are estimated at 481 million metric tons carbon equivalent—0.2 percent higher than in 1998. The relatively small increase is noteworthy because, historically, industrial energy consumption and carbon emissions have been more sensitive to economic growth than to the weather, and 1999 was a year of rapid economic growth (4.1 percent). Industrial energy consumption and emissions are concentrated in a few industries, however, and their performance may have more influence on emissions than does the performance of the industrial sector as a whole. Six industry groups—petroleum refining, chemicals and related products, primary metals, paper, food, and stone, clay and glass—collectively account for 87 percent of manufacturing energy consumption and 81 percent of carbon dioxide emissions in the industrial sector.

²Although no new nuclear facilities came on line in 1999, electricity generation from nuclear power rose to a record 728 billion kilowatt-hours, 10.5 percent above the 3-year average of 659 billion kilowatt-hours for 1996, 1997, and 1998.

³The sectoral shares of electricity-related carbon dioxide emissions are based on the shares of total electric utility power sales purchased in each sector.

⁴Population-weighted heating degree-days in 1999 were 7.4 percent lower than in 1998. See U.S. Energy Information Administration, *Annual Energy Review 1999*, DOE/EIA-0384(99) (Washington, DC, July 2000), Table 1.9.

In 1999 the six energy-intensive industry groups appeared to be still recovering from downturns from their 1997 growth rates. Their 1999 annual growth rates were lower than those for the overall economy (4.1 percent), the industrial sector (3.6 percent), and the manufacturing component of industrial production (4.3 percent). For the six energy-intensive industries, 1999 growth rates were 0.8 percent (primary metals), 2.1 percent (chemicals), 1.1 percent (paper), 2.9 percent (stone, clay and glass), 1.3 percent (petroleum), and 0.7 percent (food). The industries that grew rapidly in 1999 were primarily those with lower energy intensities, including computer equipment, which grew by 57 percent, and semiconductors and related components, which grew by 48 percent.⁵ In addition, the relatively mild weather in 1999 moderated energy consumption in industries whose energy consumption is affected by the weather, such as farming.

Carbon dioxide emissions in the transportation sector, at 496 million metric tons carbon equivalent, were 2.9 percent higher in 1999 than in 1998. Gasoline consumption, which accounted for 60 percent of transportation sector emissions, grew by 2.1 percent. Emissions from jet fuel use grew by 3.1 percent, and emissions from residual fuel (used mostly by oceangoing ships) grew by 14.6 percent. Emissions from distillate use increased by 3.8 percent, as a healthy U.S. economy led to greater consumption of diesel fuel by freight trucks.

Methane

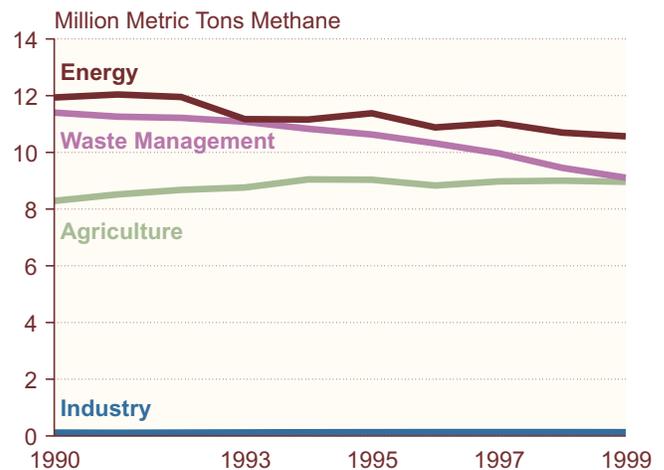
U.S. emissions of methane in 1999 were 1.8 percent lower than in 1998, at 28.8 million metric tons of methane or 165 million metric tons carbon equivalent. The decline resulted primarily from an increase in methane recovery for energy use at landfills and, to a lesser extent, from reductions in emissions from animal waste, coal mining, and petroleum systems.⁶

To be eligible for the tax credit included in Section 29 of the Windfall Profits Tax Act of 1980, methane recovery systems at landfills must have been operational by June 30, 1998. As the last recovery projects installed by the tax credit deadline came on line full time in 1999, methane recovery for energy at U.S. landfills rose from 1.7 million metric tons in 1998 to 2.1 million metric tons. In addition,

total U.S. coal production fell in 1999 for the first time in 5 years due to a drop in coal exports and nearly flat demand from electric utilities,⁷ lowering methane emissions from coal mining and post-mining activities by about 0.2 million metric tons. Domestic oil production also declined in 1999, decreasing methane emissions from petroleum systems. The drop in methane emissions from the solid waste of domesticated animals was the result of a decrease in swine populations.

Methane emissions come from four categories of sources, three major and one minor. The major sources are energy, waste management, and agriculture, and the minor source is industrial processes. The three major sources accounted for 37, 32, and 31 percent, respectively, of total 1999 U.S. emissions of methane, or approximately 9 percent of the Nation's total carbon-equivalent greenhouse gas emissions. The largest of the three major sources was energy, followed by waste management (Figure ES4). Emissions from the anaerobic decomposition of municipal solid waste in landfills, part of the waste management source category, had been declining slowly before 1999 as a consequence of a reduction in the volume of waste landfilled and a gradual increase in the volumes of landfill gas captured. Emissions of methane resulting from waste management declined by 3.7 percent in 1999.

Figure ES4. U.S. Methane Emissions by Source, 1990-1999



Sources: Estimates presented in this report.

⁵All industrial and manufacturing growth rates are taken from U.S. Federal Reserve Board, "G17 Historical Data: Industrial Production and Capacity Utilization." Although the Federal Reserve Board, in calculating indexes, bases its estimates on two main types of source data, output measured in physical units and data on inputs to the production process, it also adjusts its indexes on the basis of technological improvements in factor productivity and outputs. This could be particularly important for indexes related to computers and semiconductors, for which productivity and quality of outputs have improved dramatically over time.

⁶This year marks the first time that comprehensive estimates of methane emissions from petroleum systems appear in *Emissions of Greenhouse Gases in the United States*. Estimates of methane emissions from oil exploration and production, included in this report under the heading "Petroleum Systems," are derived from U.S. Environmental Protection Agency, Office of Air and Radiation, *Draft Estimates of Methane Emissions from the U.S. Oil Industry* (Draft Report, Washington, DC).

⁷Energy Information Administration, *U.S. Coal Supply and Demand: 1999 Review*, web site www.eia.doe.gov/fuelcoal.html.

Methane is also emitted as a byproduct of fossil energy production and transport. Methane can leak from natural gas production and distribution systems and is also emitted during coal production. Energy-related methane emissions fell by 1.2 percent in 1999. Agricultural emissions have several sources but are dominated by emissions from domestic livestock, including the animals themselves and the anaerobic decomposition of their waste. Agricultural emissions fell by about 0.4 percent in 1999.

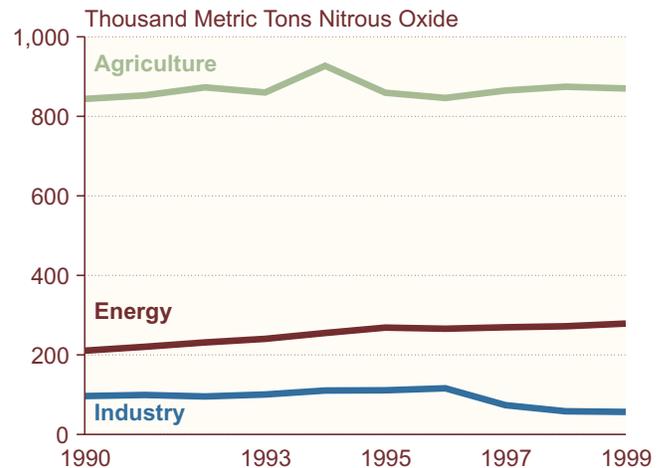
Methane emissions estimates are more uncertain than those for carbon dioxide. U.S. methane emissions do not necessarily increase with growth in energy consumption or the economy. Energy-related methane emissions are strongly influenced by coal production from a relatively restricted number of mines; agricultural emissions are influenced in part by the public's consumption of milk and beef and in part by animal husbandry practices; and livestock and municipal waste emissions are influenced by husbandry and waste management practices.

Nitrous Oxide

U.S. nitrous oxide emissions increased by 0.1 percent in 1999 compared with 1998, although the rounded total remained at 103 million metric tons carbon equivalent. Nitrous oxide accounts for 6 percent of U.S. GWP-weighted greenhouse gas emissions. Emissions estimates for nitrous oxide are more uncertain than those for either carbon dioxide or methane, because nitrous oxide is not systematically measured and many sources of nitrous oxide emissions, including nitrogen fertilization of soils and motor vehicles, require a significant number of assumptions to arrive at estimated emissions.

U.S. nitrous oxide emissions include one large class of sources and two small classes (Figure ES5). Agricultural sources account for about 71 percent of nitrous oxide emissions, and emissions associated with nitrogen fertilization of soils account for about three-quarters of agricultural emissions. In 1999, estimated nitrous oxide emissions from nitrogen fertilization of soils fell by 0.5 percent. Emissions associated with fossil fuel use account for another 23 percent of nitrous oxide emissions, of which about 82 percent comes from mobile sources, principally motor vehicles equipped with catalytic converters. The balance of nitrous oxide emissions are caused by certain chemical manufacturing and wastewater treatment processes. The most striking trend in U.S. nitrous oxide emissions has been a 51-percent decline from 1996 levels of industrial emissions of nitrous oxide after the implementation of emissions controls at an adipic acid plant operated by the DuPont Corporation.

Figure ES5. U.S. Nitrous Oxide Emissions by Source, 1990-1999



Sources: Estimates presented in this report.

Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride

The Kyoto Protocol specifies that greenhouse gas emissions, including several classes of engineered gases—HFCs, PFCs, and SF₆—be reduced. Emissions of these three classes of gases account for about 2 percent of U.S. GWP-weighted emissions of greenhouse gases. At 37.6 million metric tons carbon equivalent in 1999, their emissions were about 5 percent lower than in 1998, the first drop in emissions of such gases since a decline from 24.0 million metric tons carbon equivalent in 1990 to 22.1 million metric tons carbon equivalent in 1991.

The 1999 decline in emissions of the engineered gases was caused almost entirely by a drop in emissions of two gases, HFC-23 and SF₆. HFC-23 is emitted primarily as a byproduct during the production of HCFC-22; SF₆ is used as an insulator for electrical transmission and distribution equipment and as a cover gas in magnesium production and processing. The drop in 1999 may also be attributable in part to maturing markets for chlorofluorocarbon substitutes, stagnant markets for key high-GWP gases, and increasing awareness of the potential for recycling these gases.

Emissions of the high-GWP gases specified in the Kyoto Protocol are very small (at most a few thousand metric tons). On the other hand, some of the gases (including PFCs and SF₆) have atmospheric lifetimes measured in the hundreds or thousands of years, and consequently they are potent greenhouse gases with GWPs hundreds or thousands of times higher than that of carbon dioxide per unit of molecular weight. However, some of the commercially produced HFCs (134a, 152a, 4310, 227ea),

which are used as chlorofluorocarbon (CFC) replacements, have shorter atmospheric lifetimes of 1 to 36 years.

At 21.2 million metric tons carbon equivalent, emissions of HFCs make up the majority of this category, followed by SF₆ at 8.9 million metric tons carbon equivalent and PFCs at 4.9 million metric tons carbon equivalent. Another group of engineered gases, consisting of other HFCs, other PFCs, and perfluoropolyethers (PFPEs), includes HFC-152a, HFC-227ea, HFC-4310mee, and a variety of PFCs and PFPEs. They are grouped together in this report to protect confidential data. In 1999 their combined emissions totaled 2.6 million metric tons carbon equivalent. With the exception of the “other” group, emissions of the three major classes were lower in 1999 than in 1998, with HFCs falling by 3.8 percent, PFCs by 4.2 percent, and SF₆ by 12.7 percent. Since 1990, HFC emissions from U.S. sources have increased by 116.6 percent, PFC emissions have decreased by 25.1 percent, and SF₆ emissions have increased by 18.1 percent.

Land Use and Forestry

Forest lands in the United States are net absorbers of carbon dioxide from the atmosphere. According to U.S.

Forest Service researchers, U.S. forest land absorbs about 211 million metric tons of carbon annually, equivalent to almost 14 percent of U.S. carbon dioxide emissions. Absorption is enabled by the reversal of the extensive deforestation of the United States that occurred in the late 19th and early 20th centuries. Since then, millions of acres of formerly cultivated land have been abandoned and have returned to forest, with the regrowth of forests sequestering carbon on a large scale. The process is steadily diminishing, however, because the rate at which forests absorb carbon slows as the trees mature, and because the rate of reforestation has slowed.

Over the past several years there has been increasing interest in the United States regarding carbon sequestration in agricultural soils through changes in agricultural practices. Proponents suggest that changes in tillage practices can cause agricultural soils to move from being net sources to net sinks of carbon dioxide, and that the amounts of carbon that might be absorbed by these changes could be significant at the national level. At present, the Energy Information Administration does not have sufficient information to permit reliable estimation of national-level emissions or sequestration from this source. As more reliable information becomes available, soil carbon estimates will be included in future reports.

1. U.S. Emissions of Greenhouse Gases in Perspective

About This Report

The Energy Information Administration (EIA) is required by the Energy Policy Act of 1992 to prepare a report on aggregate U.S. national emissions of greenhouse gases for the period 1987-1990, with annual updates thereafter. This report is the seventh annual update, covering national emissions over the period 1990-1998, with preliminary estimates of emissions for 1999. The methods used by EIA to estimate national emissions of greenhouse gases are subject to continuing review. As better methods and information become available, EIA revises both current and historical emissions estimates (see "What's New in This Report," page 3). Emissions estimates for carbon dioxide are reported in metric tons of carbon; estimates for other gases are reported in metric tons of gas (see "Units for Measuring Greenhouse Gases," page 2). Total national emissions estimates measured in carbon equivalents are shown in Table ES2.

Chapter 1 of this report briefly summarizes some background information about global climate change and the greenhouse effect and discusses important recent developments in global climate change activities. Chapters 2 through 4 cover emissions of carbon dioxide, methane, and nitrous oxide, respectively. Chapter 5 focuses on emissions of engineered gases, including hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Chapter 6 describes potential sequestration and emissions of greenhouse gases as a result of land use changes.

The Greenhouse Effect and Global Climate Change

The Earth is warmed by radiant energy from the Sun. Over time, the amount of energy transmitted to the Earth's surface is approximately equal to the amount of energy re-radiated back into space in the form of

infrared radiation, and the temperature of the Earth's surface stays roughly constant; however, the temperature of the Earth is strongly influenced by the existence, density, and composition of its atmosphere. Many gases in the Earth's atmosphere absorb infrared radiation re-radiated from the surface, trapping heat in the lower atmosphere. Without the natural greenhouse effect, it is likely that the average temperature of the Earth's surface would be on the order of -19° Celsius, rather than the $+15^{\circ}$ Celsius actually observed.¹ The gases that help trap the Sun's heat close to the Earth's surface are referred to as "greenhouse gases." All greenhouse gases absorb infrared radiation (heat) at particular wavelengths.

The most important greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several engineered gases, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). Water vapor is by far the most common, with an atmospheric concentration of nearly 1 percent, compared with less than 0.04 percent for carbon dioxide. The effect of human activity on global water vapor concentrations is considered negligible, however, and anthropogenic emissions of water vapor are not factored into national greenhouse gas emission inventories for the purposes of meeting the requirements of the United Nations Framework Convention on Climate Change (FCCC) or the Kyoto Protocol.² Concentrations of other greenhouse gases, such as methane and nitrous oxide, are a fraction of that for carbon dioxide (Table 1).

Scientists recognized in the early 1960s that concentrations of carbon dioxide in the Earth's atmosphere were increasing every year. Subsequently, they discovered that atmospheric concentrations of methane, nitrous oxide, and many engineered chemicals also were rising. Because current concentrations of greenhouse gases keep the Earth at its present temperature, scientists began to postulate that increasing concentrations of greenhouse gases would make the Earth warmer.

¹Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 57. See also web site www.ipcc.ch. It is important to note that the IPCC's third assessment report is scheduled for release in early 2001.

²The United Nations Framework Convention on Climate Change, which "entered into force" in 1994, calls on Annex I countries, including the United States, to return their greenhouse gas emissions to 1990 levels by the year 2000. The Kyoto Protocol, adopted in December 1997, is a set of quantified greenhouse gas emissions targets for Annex I countries for the 2008 to 2012 commitment period that are collectively about 5 percent lower than the 1990 emissions of those countries. The Protocol has not yet "entered into force," which would require 55 countries and Annex I signatories with carbon dioxide emissions totaling 55 percent of total Annex I emissions to ratify the Protocol. The United States has not yet ratified the Protocol.

Table 1. Global Atmospheric Concentrations of Selected Greenhouse Gases

Item	Carbon Dioxide	Methane	Nitrous Oxide	Sulfur Hexafluoride	Perfluoromethane
	(parts per million)			(parts per trillion)	
Preindustrial Atmospheric Concentration	278	0.700	0.275	0	0
1992 Atmospheric Concentration	356	1.714	0.311	32	70
Average Annual Change, Recent Years ^a	1.6	0.008	0.0008	0.2	1.2
Average Percent Change, Recent Years ^a	0.4	0.6	0.25	0.6	1.7
Atmospheric Lifetime (Years)	50–200	12	120	3,200	50,000

^aIPCC best estimate for recent years leading up to 1995.

Source: Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), pp. 92-93.

Units for Measuring Greenhouse Gases

In this publication, EIA reports information in forms that are most likely to be familiar to users of the document. Therefore, energy and industrial data are reported in their native units. For example, oil production is reported in thousand barrels per day, and energy production and sales are reported in British thermal units (Btu). For readers familiar with metric units, Btu can be a relatively intuitive unit because an exajoule is only 5 to 6 percent larger in energy content than a quadrillion Btu.

Emissions data are reported in metric units. This report uses the familiar “million metric tons” common in European industry instead of “gigagram,” which is equal to 1,000 metric tons and is the term favored by the scientific community. Metric tons are also relatively intuitive for users of English units, because a metric ton is only about 10 percent heavier than an English short ton.

Emissions of most greenhouse gases are reported here in terms of the full molecular weight of the gas (as in Table ES1). In Table ES2, however, and subsequently throughout the report, carbon dioxide is reported in carbon units, defined as the weight of the carbon content of carbon dioxide (i.e., just the “C” in CO₂). Carbon dioxide units at full molecular weight can be converted into carbon units by dividing by 44/12, or 3.6667. This approach has been adopted for two reasons:

- Carbon dioxide is most commonly measured in carbon units in the scientific community. Scientists

argue that not all carbon from combustion is, in fact, emitted in the form of carbon dioxide. Because combustion is never perfect, some portion of the emissions consists of carbon monoxide, methane, other volatile organic compounds, and particulates. These other gases (particularly carbon monoxide) eventually decay into carbon dioxide, but it is not strictly accurate to talk about “tons of carbon dioxide” emitted.

- Carbon units are more convenient for comparisons with data on fuel consumption and carbon sequestration. Because most fossil fuels are 75 percent to 90 percent carbon by weight, it is easy and convenient to compare the weight of carbon emissions (in carbon units) with the weight of the fuel burned. Similarly, carbon sequestration in forests and soils is always measured in tons of carbon, and the use of carbon units makes it simple to compare sequestration with emissions.

While carbon dioxide emissions can be measured in tons of carbon, emissions of other gases (such as methane) can also be measured in “carbon dioxide equivalent” units by multiplying their emissions (in metric tons) by their global warming potentials (GWPs). GWPs are discussed later in this chapter and summarized in Table 3. For comparability, carbon dioxide equivalent units can be converted to “carbon equivalent” by multiplying by 12/44 (as in Table ES2) to provide a measure of the relative effects of various gases on climate.

What's New in This Report

Chapter 2: Carbon Dioxide Emissions

- Military bunker fuels are included as an adjustment to total energy consumption. Under international protocol, fuels consumed in international waters or on international flights are subtracted from a country's total energy consumption, and the resulting emissions estimate is reduced by the corresponding amount of carbon dioxide. The U.S. Environmental Protection Agency (EPA) has estimated military bunker fuel consumption most recently for 1998. The EPA's 1998 estimate (2.7 million metric tons carbon equivalent) is used here for both 1998 and 1999, because there has been little annual change in the estimates for recent years.
- Greenhouse gas emissions from plastics contained in municipal solid waste (MSW) that is combusted are also included. Although much of the MSW that is combusted is for electricity generation, the number is included under other sources in this report in keeping with international protocol.
- In keeping with the revised guidelines of the Intergovernmental Panel on Climate Change (IPCC), published in 1996 and updated at an IPCC Expert Working Group Meeting on Good Practices in Inventory Preparation held in the United Kingdom in October 1999, an analysis of the uncertainty in the energy-related carbon dioxide emissions data was conducted using a Monte Carlo analysis. A summary of the results of the analysis is included in Chapter 2.

Chapter 3: Methane Emissions

- Revised estimates of methane emissions from petroleum production, transportation, and refining operations are included.

Chapter 5: Other Gases: Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride

- Historical emissions for a group of gases including HFC-152a, HFC-227ea, HFC-4310mee, and a variety of PFCs and perfluoropolyethers (PFPEs) have been revised. Emissions of these substances are considered confidential by the U.S. Environmental Protection Agency (EPA) and are published only in total for the group as a whole, in metric ton

carbon equivalent units. Last year, emissions of each of these substances were estimated by EIA, based on extrapolation of trends shown in earlier published estimates. This year, EIA has adopted the EPA's emissions estimates for this group of substances. The new estimates have the effect of reducing overall carbon-equivalent emissions of HFCs and PFCs by approximately 9 percent from 1995 to 1999, and by smaller amounts prior to 1995.

- Emissions data on non-Kyoto gases, including ozone-depleting substances and criteria pollutants, are no longer included in this chapter. Because the impact of ozone-depleting substances on climate is ambiguous and the role of criteria pollutants in climate change is indirect, the chapter focuses only on those greenhouse gases that are to be reduced under the United Nations Framework Convention on Climate Change.

Chapter 6: Land Use Issues

- Revisions to the land use chapter reflect the results of a recent IPCC special report on land use, land use changes, and forestry (LULUCF).^a

Appendixes

- The previous EIA reports on U.S. greenhouse gas emission inventories included six appendixes. This year, in keeping with EIA's Strategic Plan for electronic dissemination of EIA data, those appendixes are not included in the print version of the report but instead are being made available for viewing and/or download at web site www.eia.doe.gov/oiaf/1605/ggrpt/index.html. Appendix A provides a detailed discussion of emissions sources, estimation methods, and data requirements and sources. Appendix B describes the derivation of the greenhouse gas emissions coefficients used for this report. Appendix C describes uncertainties in the emissions estimates. Appendix D describes known emissions sources omitted from the main report because they are not deemed to be "anthropogenic," or because of excessive uncertainty. Appendix E provides an historical time series of U.S. carbon dioxide emissions. Appendix F provides common conversion factors.

^aIntergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), web site www.ipcc.ch/pub/srlulucf-e.pdf.

In computer-based simulation models, rising concentrations of greenhouse gases nearly always produce an increase in the average temperature of the Earth. Rising temperatures may, in turn, produce changes in weather and in the level of the oceans that might prove disruptive to current patterns of land use and human settlement, as well as to existing ecosystems. To date, it has proved difficult to detect firm evidence of actual temperature changes, in part because the normal temporal and spatial variations in temperature are far larger than the predicted change in the global average temperature. Even when temperature changes are identified, it is not possible to be certain whether they are random fluctuations that will reverse themselves or the beginning of a trend. The possible effects of rising temperatures on weather patterns are even more uncertain.

The most recent report of the IPCC, an international assemblage of scientists commissioned by the United Nations to assess the scientific, technical, and socioeconomic information relevant for the understanding of the risk of human-induced climate change, concluded that:

Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitudes and patterns of long-term variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land surface changes. Nevertheless, the balance of evidence suggests that there is a discernable human influence on global climate.³

While both the existence and consequences of human-induced global climate change remain uncertain, the threat of climate change has put in motion an array of

efforts by the United States and other governments to find some mechanism for limiting the risk of climate change and ameliorating possible consequences. To date, efforts have focused on identifying levels and sources of emissions of greenhouse gases and on possible mechanisms for reducing emissions or increasing sequestration of greenhouse gases.

Global Sources of Greenhouse Gases

Most greenhouse gases have natural sources in addition to human-made sources, and there are natural mechanisms for removing them from the atmosphere. However, the continuing growth in atmospheric concentrations establishes that, for each of the major greenhouse gases, more gas is being emitted than is being absorbed each year: that is, the natural absorption mechanisms are lagging behind. Table 2 illustrates the relationship between anthropogenic (human-made) and natural emissions and absorption of the principal greenhouse gases.

Water Vapor. Water vapor, as noted above, is the most common greenhouse gas present in the atmosphere. It is emitted into the atmosphere in enormous volumes through natural evaporation from oceans, lakes, and soils and is returned to Earth in the form of rain and snow. Water vapor is so plentiful in the atmosphere that additional emissions are unlikely to absorb any significant amount of infrared radiation. It is also likely that the amount of water vapor held in the atmosphere is generally in equilibrium, and that increasing emissions of water vapor would not increase atmospheric concentrations.⁴ According to currently available information, anthropogenic water vapor emissions at the Earth's surface are unlikely to be an important element in either causing or ameliorating climate change.

Table 2. Global Natural and Anthropogenic Sources and Absorption of Greenhouse Gases

Gas	Sources		Absorption	Annual Increase in Gas in the Atmosphere
	Natural	Human-Made		
Carbon Dioxide (Million Metric Tons of Carbon)	150,000	7,100	154,000	3,100–3,500
Methane (Million Metric Tons of Gas)	110–210	300–450	460–660	35–40
Nitrous Oxide (Million Metric Tons of Gas).	6–12	4–8	10–17	3–5

Sources: Carbon dioxide estimates for “Human-Made Sources” and “Annual Increase in Gas in the Atmosphere” are summarized from ranges appearing in Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 17, Table 2. Carbon dioxide estimates for “Natural Sources” and “Absorption” are summarized from calculations in Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 77, Figure 2.1. Methane estimates are summarized from ranges appearing in Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 18, Table 3. Nitrous oxide estimates are summarized from ranges appearing in Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emissions Scenarios* (Cambridge, UK; Cambridge University Press, 1995), p. 90, Table 2.4.

³Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 5.

⁴Note, however, that changing air temperature from other causes will change the equilibrium amount of water vapor contained in the atmosphere. This may be a “feedback” effect acting to accelerate or slow global climate change.

Carbon Dioxide. Carbon is a common element on the planet, and immense quantities can be found in the atmosphere, in soils, in carbonate rocks, and dissolved in ocean water. All life on Earth participates in the “carbon cycle,” by which carbon dioxide is extracted from the air by plants and decomposed into carbon and oxygen, with the carbon being incorporated into plant biomass and the oxygen released to the atmosphere. Plant biomass, in turn, ultimately decays (oxidizes), releasing carbon dioxide back into the atmosphere or storing organic carbon in soil or rock. There are vast exchanges of carbon dioxide between the ocean and the atmosphere, with the ocean absorbing carbon from the atmosphere and plant life in the ocean absorbing carbon from water, dying, and spreading organic carbon on the sea bottom, where it is eventually incorporated into carbonate rocks such as limestone.

Records from Antarctic ice cores indicate that the carbon cycle has been in a state of imbalance for the past 200 years, with emissions of carbon dioxide to the atmosphere exceeding absorption. Consequently, carbon dioxide concentrations in the atmosphere have been steadily rising.

The most important natural sources of carbon dioxide are releases from the oceans (90 billion metric tons per year), aerobic decay of vegetation (30 billion metric tons), and plant and animal respiration (30 billion metric tons).⁵ Known anthropogenic sources (including deforestation) were estimated to account for about 7 billion metric tons of carbon per year in the early 1990s. The principal anthropogenic source is the combustion of fossil fuels, which accounts for about three-quarters of total anthropogenic emissions of carbon dioxide worldwide. Natural processes—primarily, uptake by the ocean and photosynthesis—absorb substantially all the naturally produced carbon dioxide and some of the anthropogenic carbon dioxide, leading to an annual net increase in carbon dioxide in the atmosphere of 3.1 to 3.5 billion metric tons.⁶

Methane. Methane is also a common compound. The methane cycle is less well understood than the carbon cycle. Natural methane is released primarily by anaerobic decay of vegetation, by the digestive tracts of termites in the tropics, and by several other lesser sources. The principal anthropogenic sources are leakages from the production of fossil fuels, human-promoted anaerobic decay in landfills, and the digestive processes of domestic animals. The main sources of absorption are thought to be decomposition (into carbon dioxide) in the atmosphere and decomposition by bacteria in soil. Known and unknown sources of methane are estimated

to total about 600 million metric tons annually; known sinks (i.e., absorption by natural processes) total about 560 million metric tons. The annual increase in methane concentration in the atmosphere accounts for the difference of 35 to 40 million metric tons.

Nitrous Oxide. The sources and absorption of nitrous oxide are much more speculative than those for other greenhouse gases. The principal natural sources are thought to be bacterial breakdown of nitrogen compounds in soils, particularly forest soils, and fluxes from ocean upwellings. The primary human-made sources are enhancement of natural processes through application of nitrogen fertilizers, combustion of fuels, and certain industrial processes. The existence of significant unidentified sources of nitrous oxide has set off a search for new sources, one consequence of which has been recent revisions to the IPCC emissions estimations methods for nitrous oxide from nitrogen fertilization of soils. The most important sink is thought to be decomposition in the stratosphere. Worldwide, estimated known sources of nitrous oxide total 13 to 20 million metric tons annually, and known sinks total 10 to 17 million metric tons. The annual increase in concentrations in the atmosphere is thought to total about 3 to 5 million metric tons.

Halocarbons and Other Gases. During the twentieth century, human ingenuity created an array of “engineered” chemicals, not normally found in nature, whose special characteristics render them particularly useful. Some engineered chemicals are also greenhouse gases. The best known are the chlorofluorocarbons (CFCs), particularly CFC-12, often known by its trade name, “Freon-12.” CFCs have many desirable features: they are relatively simple to manufacture, inert, nontoxic, and nonflammable. Because CFCs are chemically stable, once emitted, they remain in the atmosphere for hundreds or thousands of years. Because they are not found in nature, these molecules absorb reflected infrared radiation at wavelengths that otherwise would be largely unabsorbed, and they are potent greenhouse gases, with a direct radiative forcing effect hundreds or thousands of times greater, gram-per-gram, than that of carbon dioxide.

Because of their long atmospheric lives, a portion of the CFCs emitted into the atmosphere eventually find their way into the stratosphere, where they can be destroyed by sunlight. This reaction, however, releases free chlorine atoms into the stratosphere, and the free chlorine atoms tend to combine with stratospheric ozone, which protects the surface of the Earth from certain wavelengths of potentially damaging solar ultraviolet radiation (ultraviolet radiation, for example, causes human

⁵Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 77.

⁶One metric ton equals 1.102 short tons.

and animal skin cancers). The destruction of stratospheric ozone, notwithstanding its potential damage to living organisms, exerts a net cooling effect on the surface of the planet, making the net effects of CFCs on radiative forcing ambiguous.

The threat posed by CFCs to the ozone layer has caused the United States and many other countries to commit themselves to phasing out the production of CFCs and their chemical cousins, hydrochlorofluorocarbons (HCFCs), pursuant to an international treaty, the 1987 Montreal Protocol. As use of CFCs has declined, many related chemicals have emerged as alternatives, including HCFCs and hydrofluorocarbons (HFCs). HCFCs are similar to CFCs, but they are more reactive and consequently have shorter atmospheric lives, with less effect on the ozone layer and smaller direct global warming effects. HCFCs are also being phased out, but over a much longer time scale.

HFCs have no chlorine and consequently have no effect on the ozone layer, but they have potentially powerful direct effects on climate. HFCs were rare before 1990, but in 1994 HFC-134a was adopted as the standard motor vehicle air conditioning refrigerant in virtually all new cars made in America. Consequently, HFC emissions are now rising rapidly, though from a negligible base.

Another new class of engineered halocarbons are the perfluorocarbons (PFCs), which include CF_4 , C_2F_6 , and C_3F_8 . PFCs are emitted as byproducts of aluminum smelting and are increasingly being used in the manufacture of semiconductors.

Sulfur hexafluoride (SF_6) is used as an insulator in utility-scale electrical equipment and as a cover gas in magnesium smelting. It is not a halocarbon, but it is a powerful greenhouse gas. Other chemicals not yet identified may exhibit similar radiative properties. All of these chemicals are potent greenhouse gases because they combine high radiative properties with very long atmospheric lifetimes.

The solvents carbon tetrachloride, methyl chloroform, and methylene chloride are regulated in the United States both as ozone depleters and for toxicity. All these gases have direct radiative forcing effects, which are offset to some degree by their ozone-depleting effects.

With the advent of the Framework Convention and the Kyoto Protocol, the halocarbon and other industrial chemicals can be grouped into two categories:

- Ozone-depleting chemicals regulated under the Montreal Protocol but excluded from the Framework Convention (CFCs, HCFCs, and others)

- “Kyoto Protocol gases” (HFCs, PFCs, and sulfur hexafluoride).

The “Kyoto Protocol gases” are deemed to “count” for climate change policy analysis. The ozone depleters generally are excluded, because they are dealt with elsewhere.

Radiatively Important Gases. In addition there are a set of man-made pollutants, emitted primarily as byproducts of combustion (both of fossil fuels and of biomass), that have indirect effects on global warming: carbon monoxide, nitrogen oxides, nonmethane volatile organic compounds (NMVOCs), and sulfur dioxide. These compounds, regulated in the United States pursuant to the Clean Air Act, are often referred to (along with particulates and lead) as “criteria pollutants.” The criteria pollutants are reactive compounds, and they tend to remain in the atmosphere for only hours or days. The sequence of reactions that removes carbon monoxide, nitrogen oxides, and NMVOCs from the atmosphere, however, tends to promote the formation of ozone (O_3), a reactive and unstable molecular form of oxygen. Ozone in the stratosphere protects life on Earth from ultraviolet radiation, but ozone at ground level in high concentrations causes respiratory distress in people and animals and, also, is itself a potent (though short-lived) greenhouse gas.⁷

It has not proved possible to make a general determination of the contribution of ozone precursors to global warming. The reactions that produce ozone are strongly affected by the relative concentrations of various pollutants, the ambient temperature, and local weather conditions. Emissions of criteria pollutants can create very high, though localized, ozone concentrations under favorable conditions (for example, a warm, sunny day combined with still air and low humidity) and negligible concentrations under unfavorable conditions.

Sulfur dioxide, on the other hand, probably exerts a net cooling effect on the climate. Sulfur dioxide creates tiny solid particles (aerosols) in the atmosphere, which in turn act as nuclei for collections of water droplets and stimulate cloud formation. The clouds, in turn, reflect sunlight back into space, cooling the planet. The most important such gas is sulfur dioxide (SO_2), which is emitted largely as a byproduct from the combustion of sulfur-containing fossil fuels, particularly coal. Sulfur dioxide reacts in the air to form sulfate compounds that are effective in promoting cloud formation. Sulfur dioxide emissions are regulated in the United States under the Clean Air Act, and their concentrations have declined considerably in recent years. Particulate

⁷The U.S. Environmental Protection Agency has set a National Ambient Air Quality Standard for acceptable atmospheric concentrations of ozone at 0.12 parts per million. The standard was set on the basis that concentrations of this magnitude could cause respiratory distress in vulnerable individuals. Higher concentrations (above 0.3 parts per million) would cause respiratory distress for most individuals.

emissions are also likely to exert a net cooling effect by promoting cloud formation.

Relative Forcing Effects of Various Gases

Some greenhouse gases are more potent in affecting global temperatures than are others. As a result, comparable increases in the concentrations of different greenhouse gases can have vastly different heat-trapping effects. Among those identified, carbon dioxide is among the least effective as a greenhouse gas. Other compounds, on a gram-per-gram basis, appear to have much greater effects.⁸

There has been extensive study of the relative effectiveness of various greenhouse gases in trapping the Earth's heat. Such research has led to the development of the concept of a "global warming potential," or GWP. The GWP is intended to illustrate the relative impacts on global warming of various gases, compared with that of carbon dioxide. Over the past few years, the IPCC has conducted an extensive research program aimed at summarizing the effects of various greenhouse gases through a set of GWPs. The results of that work were released in 1995 in an IPCC report, *Climate Change 1994*⁹ and updated in *Climate Change 1995*.¹⁰

- Each gas absorbs radiation in a particular set of wavelengths, or "window," in the spectrum. In some cases, where concentrations of the gas are low and no other gases block radiation in the same window, small emissions of the gas will have a disproportionate absorptive effect. However, if concentrations of the gas rise over time, a larger and larger portion of the total light passing through the "window" will already have been captured, and the marginal effects of additional emissions will not be as large. Therefore, the effect of an additional unit of emission of a gas that is relatively plentiful in the atmosphere, such as water vapor or carbon dioxide, tends to be less than that of a rare gas, such as sulfur hexafluoride. This "diminishing return" effect implies that increasing the concentration of a particular gas reduces the impact of additional quantities of that gas. Thus, the relative impacts of various gases will change as their relative concentrations in the atmosphere change.
- Various natural processes cause many greenhouse gases to decompose into other gases or to be

absorbed by the ocean or ground. These processes can be summarized in terms of the "atmospheric lifetime" of a particular gas, or the period of time it would take for natural processes to remove a unit of emissions from the atmosphere. Some gases, such as CFCs, have very long atmospheric lifetimes, in the hundreds of years. Others, such as carbon monoxide, have lives measured in hours or days. Methane, which decays into carbon dioxide over a period of a few years, has a much larger short-run effect on global warming than does an equivalent amount of carbon dioxide; however, over longer and longer periods—from 10 years to 100 years to 500 years, for example—the differences between the GWPs of methane and carbon dioxide become less significant.

- Many gases are chemically active, and they may react in the atmosphere in ways that promote or hinder the formation of other greenhouse gases. For example, nitrogen oxides and carbon monoxide combine to promote the formation of tropospheric ozone, whereas CFCs tend to destroy stratospheric ozone, thus promoting global cooling. Such indirect effects have sometimes proved difficult to summarize in terms of global warming potentials. Indirect effects also imply that changes in relative concentrations of various greenhouse gases would tend to change their relative effects.

Despite such complexity, the scientific community is working to develop GWP approximations. Table 3 summarizes the consensus results of the most recent studies by scientists working on behalf of the IPCC, showing estimates of atmospheric lifetimes and global warming potentials across various time scales. For the purposes of calculating "carbon dioxide equivalent" units for this report, 100-year GWPs are used.

The IPCC has also devoted effort to the study of indirect and interactive effects of various gases—particularly the indirect effects of CFCs and HCFCs on the ozone layer—compared with their direct radiative forcing effects. The IPCC presented GWP estimates for the first time in 1996 that quantified the direct and indirect effects of certain CFCs and HCFCs. Certain chemicals (halon-1301 and carbon tetrachloride, for example) are now believed to exert a net cooling influence—i.e., to have a negative GWP. All the net GWPs for CFCs and HCFCs are considerably lower than their direct GWPs.¹¹

⁸Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 22.

⁹Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiative Forcing of Climate Change* (Cambridge, UK: Cambridge University Press, 1995).

¹⁰Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

¹¹Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 122.

Table 3. Numerical Estimates of Global Warming Potentials Compared With Carbon Dioxide
(Kilogram of Gas per Kilogram of Carbon Dioxide)

Gas	Lifetime (Years)	Direct Effect for Time Horizons of		
		20 Years	100 Years	500 Years
Carbon Dioxide	Variable	1	1	1
Methane.	12 ± 3	56	21	7
Nitrous Oxide	120	280	310	170
HFCs, PFCs, and Sulfur Hexafluoride				
HFC-23	264	9,200	12,100	9,900
HFC-125	33	4,800	3,200	11
HFC-134a	15	3,300	1,300	420
HFC-152a	2	460	140	42
HFC-227ea	37	4,300	2,900	950
Perfluoromethane	50,000	4,400	6,500	10,000
Perfluoroethane	10,000	6,200	9,200	14,000
Sulfur Hexafluoride	3,200	16,300	23,900	34,900

Note: The typical uncertainty for global warming potentials is estimated by the Intergovernmental Panel on Climate Change at ±35 percent.

Source: Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), p. 121.

Global Climate Change International Developments

Rising concentrations of carbon dioxide in the atmosphere were first detected in the late 1950s, and observations of atmospheric concentrations of methane, nitrous oxide, and other gases began in the late 1970s. Concern about the effects of rising atmospheric concentrations of greenhouse gases remained largely the province of atmospheric scientists and climatologists, however, until the mid-1980s, when a series of international scientific workshops and conferences began to move the topic onto the agenda of United Nations specialized agencies, particularly, the World Meteorological Organization (WMO).

The IPCC was established under the auspices of the United Nations Environment Program and the WMO in late 1988, to accumulate available scientific research on climate change and to provide scientific advice to policymakers. A series of international conferences provided impetus for an international treaty aimed at limiting the human impact on climate. In December

1990, the United Nations established the Intergovernmental Negotiating Committee (INC) for a Framework Convention on Climate Change. Beginning in 1991, the INC hosted a series of negotiating sessions that culminated in the adoption, by more than 160 countries, including the United States, of the Framework Convention on Climate Change (FCCC), opened for signature at the “Earth Summit” in Rio de Janeiro, Brazil on June 4, 1992.¹²

From the Framework Convention to the Kyoto Protocol

The objective of the Framework Convention is stated as follows:

The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.¹³

¹²The Framework Convention was “adopted” by a vote of the conference of the parties on May 9th, while the signatures and ratifications of member states flowed in over a period of years. The treaty “entered into force” in 1994. There is a discussion of the development of the Convention in D. Bodanzky, “Prologue to the Climate Convention,” in I. Mintzer and J.A. Leonard (eds.), *Negotiating Climate Change: The Inside Story of the Rio Convention* (Cambridge, UK: Cambridge University Press, 1994), pp. 49-66.

¹³The official text of the Framework Convention can be found at web site www.unfccc.de/index.html.

The Framework Convention divided its signatories into two groups: the countries listed in Annex I to the Protocol, and all others. The Annex I countries are developed industrial states: the United States, Eastern and Western Europe, Russia and the Ukraine, Japan, Australia, New Zealand, and Canada.¹⁴

The Convention requires all parties to undertake “policies and measures” to limit emissions of greenhouse gases, and to provide national inventories of emissions of greenhouse gases (Article 4.1a and b). Annex I parties are further required to take actions “with the aim of returning . . . to their 1990 levels these anthropogenic emissions of carbon dioxide and other greenhouse gases” (Article 4.2a and b). The signatories subsequently agreed that Annex I parties should provide annual inventories of greenhouse gas emissions.

In April 1993, President Clinton committed to stabilizing U.S. emissions of greenhouse gases at the 1990 level by 2000, using an array of voluntary measures. In the following years, however, greenhouse gas emissions in the United States and many other Annex I countries continued to increase. The climate negotiators, continuing to meet as “the Conference of the Parties [to the Framework Convention]” (COP), took up the question of how to limit emissions in the post-2000 period, a topic on which the Framework Convention was silent. In 1995, COP-1, held in Berlin, Germany, agreed to begin negotiating a post-2000 regime. In 1996, COP-2, held in Geneva, Switzerland, agreed that the regime would encompass binding limitations on emissions for the parties, to be signed at COP-3, which was held in Kyoto, Japan, in December 1997.

The Kyoto Protocol

The most fundamental feature of the Kyoto Protocol to the Framework Convention, adopted on December 11, 1997, is a set of quantified greenhouse gas emissions targets for Annex I countries, which collectively are about 5 percent lower than the 1990 emissions of those countries taken as a group.¹⁵ Developing country signatories do not have quantified targets. Some of the key features of the Protocol are summarized below:

- **Differentiated Targets.** Each Annex I signatory has a “quantified emissions reduction limitation commitment,” which limits the signatory to some

fraction, ranging from 90 to 110 percent, of its 1990 greenhouse gas emissions.¹⁶ Both the European Union (EU) and the individual members of the EU signed the Protocol and are responsible for meeting their commitments.

- **Commitment Period.** Each target is defined as the average of the signatory’s emissions over the 5-year period 2008-2012, called “the commitment period.”
- **Six Gases.** Participants are to limit their emissions of carbon dioxide, methane, nitrous oxide, HFCs, PFCs, and sulfur hexafluoride, weighted by the GWP of each gas. HFCs and PFCs are actually classes of gases with multiple members, but the term “six gases” has stuck. Participants may use 1995 as the baseline for HFCs, PFCs, and sulfur hexafluoride, instead of 1990.
- **Demonstrable Progress.** Annex I countries are required to have made “demonstrable progress” toward achieving their commitments by 2005.
- **Land Use and Forestry.** The Protocol includes complicated provisions on forestry, the implication being that some emissions and sequestration arising from changes in land use and forestry since 1990 can be counted against the target.
- **Flexibility Mechanisms.** The Protocol includes an array of methods by which Annex I countries can spread and reduce the cost of emissions limitations. The flexibility mechanisms include:
 - **Emissions Trading.** Annex I countries can transfer portions of their emissions targets to one another.
 - **Joint Implementation.** Annex I countries can undertake emissions reduction projects in other Annex I countries and receive a negotiated share of the emissions reductions generated by the projects.
 - **Joint Fulfillment.** Like-minded Annex I countries (such as the EU) may band together to reallocate national targets within the group, so long as the collective target is met.
 - **Clean Development Mechanism.** Annex I countries may undertake emissions reduction projects in non-Annex I countries and receive credits countable against national targets.

¹⁴The Annex I grouping has undergone a number of changes. Russia, the Ukraine, Latvia, Estonia, and Lithuania (but not the Central Asian Republics) are now part of Annex I. Belarus participated for a while but did not join the Kyoto Protocol. Turkey initially joined the Convention but subsequently asked to withdraw from Annex I status and did not join the Kyoto Protocol. Czechoslovakia has divided into the Czech Republic and Slovakia, and two Yugoslav successor states, Croatia and Slovenia, have joined Annex I. Lichtenstein and Monaco have also joined the Kyoto Protocol. In June 1999, Kazakhstan applied for Annex I status but subsequently withdrew its application in June 2000.

¹⁵The text of the Kyoto Protocol can also be found at web site www.unfccc.de/index.html.

¹⁶Several Eastern European states have been permitted to use emissions from the late 1980s, rather than 1990, as their baseline. All signatories may elect to use 1995 emissions of HFCs, PFCs, and sulfur hexafluoride as the baseline rather than 1990 emissions.

- **Entry into Force.** The Protocol enters into force when 55 countries and Annex I signatories with carbon dioxide emissions totaling 55 percent of total Annex I emissions “have deposited their instruments of ratification, acceptance, approval, or accession.” As of September 2000, 84 countries (including 25 Annex I countries) had signed (not ratified) the Protocol. Thirty countries (many of them small island states) have ratified the Protocol to date.

The Kyoto Protocol and the United States

The U.S. Government formally signed the Kyoto Protocol on November 12, 1998. Under the U.S. Constitution, however, the Government may adhere to treaties only with the “advice and consent” of the Senate.¹⁷ The Protocol has not yet been sent to the Senate. The view of the Executive Branch was expressed by the White House Press Secretary:

*Signing does not legally commit the United States to implement the Protocol. The Protocol would become binding only with the advice and consent of the U.S. Senate. President Clinton has made clear that the United States regards the Kyoto Protocol as a work in progress, and that it will not be submitted for ratification without the meaningful participation of key developing countries in efforts to address climate change.*¹⁸

Beyond the Kyoto Protocol

Since the signing of the Kyoto Protocol, the signatories have continued to shape the “work in progress.” The Conference of the Parties met in November 1998 in Buenos Aires, Argentina (COP-4) and in October and November 1999 in Bonn, Germany (COP-5) and will meet again in November 2000 in The Hague, Netherlands (COP-6). The two “subsidiary bodies” of the Conference of the Parties, the Subsidiary Body for Implementation (SBI) and Subsidiary Body for Scientific and Technological Advice (SBSTA), meanwhile, met in advance of COP-6 in September 2000 in Lyon, France, to discuss such matters as land use changes, capacity building in developing countries, and “best practices” in policies.

There are, however, still many implementation issues dividing Kyoto Protocol signatories—including “supplementarity,” the role of developing countries in meeting the Protocol’s goals, and what greenhouse gas

mitigation credits should be granted for land use, land use changes, and forestry (LULUCF). The term “supplementarity” is derived from Article 17 of the Protocol, which in describing emissions trading says, “Any such trading shall be *supplemental* to domestic actions for the purpose of meeting quantified emission limitation and reduction commitments under that Article.” A similar sentence is included in Article 6 (Joint Implementation), and somewhat similar language (“... contribute to compliance . . .”) is included in Article 12 (Clean Development Mechanism). The European Union (EU) takes the position that “supplemental” in this context means that emissions reductions achieved through trading, joint implementation, and/or the Clean Development Mechanism should account for only a limited portion of national emissions reductions under the Protocol, and that this limit should be quantified and spelled out. The view of the U.S. Government is that no such limit was intended, and that imposing a “sublimit” would raise the cost of compliance without providing any environmental benefit.

Another piece of unresolved business from Kyoto is the status of developing countries. Their status under the Kyoto Protocol itself is fairly clear: they do not have quantitative obligations, but they may participate in emissions reduction projects through the Clean Development Mechanism. The U.S. Government, however, has set “meaningful participation” by developing countries as a condition for submitting the Protocol to the Senate for ratification. At the Buenos Aires meeting, two developing countries, Argentina and Kazakhstan, agreed to take on voluntary emissions limitation targets. Bolivia has also subsequently agreed to take on voluntary targets. Kazakhstan, which applied for Annex I status in 1999, withdrew its application in 2000. Developing countries as a group, led by China and the so-called “Group of 77” (G77), have expressed opposition to the acceptance by any developing country of an emissions limitation target, even voluntarily, arguing that this is a violation of the principle of “common but differentiated” responsibilities articulated in the Framework Convention.¹⁹

Signatories also are divided as to the extent to which countries can meet their Protocol commitments through LULUCF projects. Because the extent to which a country can use LULUCF projects to meet its commitments will directly affect its compliance costs, the issue has engendered a division among signatory countries. Some

¹⁷ Article II, Section 2, of the Constitution reads, in part: “He [the President] shall have power, by and with the advice and consent of the Senate, to make treaties, provided two thirds of the Senators present concur”

¹⁸ Statement by the Press Secretary, the White House, November 12, 1998. See web site www.whitehouse.gov.

¹⁹ This difference of view manifested itself at the fourth meeting of the Conference of the Parties in Buenos Aires in November 1998. The Argentine government expressed a desire to accept voluntarily an emissions reduction commitment, and the United States and other governments asked that the question of voluntary commitments be placed on the agenda for discussion. China and the “Group of 77” developing countries opposed inclusion of this item on the conference agenda, and the topic was not formally discussed. See *Position Paper of the Group of 77 and China on the Provisional Agenda*, FCCC/SBI/1998/MISC.3, web site www.unfccc.de/resource/docs/1998/sbi/misc03.htm.

countries with large carbon sinks in the form of forested lands, such as the United States, Australia, Canada, and Norway, strongly support the inclusion of LULUCF mechanisms for meeting national commitments. The EU, meanwhile, has attempted to limit the extent to which LULUCF can be used to meet the commitments, and the G77 countries have tried to limit LULUCF to human-induced activities. On August 1, 2000, the United States submitted its views on LULUCF to the

FCCC in advance of COP-6, where further decisions on LULUCF will be made. The U.S. position proposes the inclusion of forest management, cropland management, and grazing land management as LULUCF mechanisms to capture carbon and meet future Kyoto commitments. The U.S. proposal includes a phase-in period during which LULUCF carbon removals would be discounted and only counted above a predetermined threshold level.

2. Carbon Dioxide Emissions

Overview

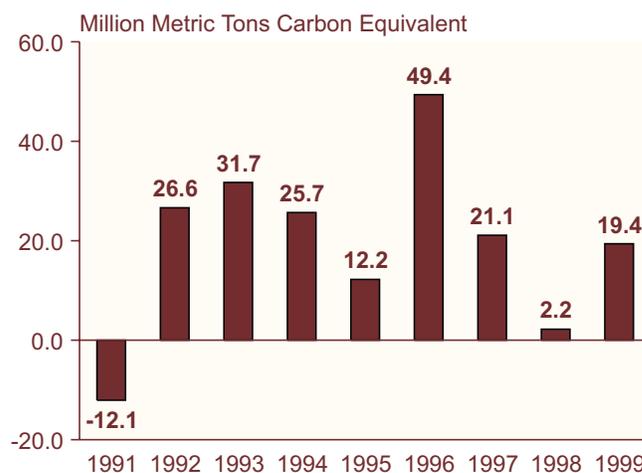
U.S. Anthropogenic Carbon Dioxide Emissions, 1990-1999		
	Carbon Dioxide	Carbon Equivalent
Estimated 1999 Emissions (Million Metric Tons)	5,598.7	1,526.8
Change Compared to 1998 (Million Metric Tons)	71.1	19.4
Change from 1998 (Percent)	1.3%	1.3%
Change Compared to 1990 (Million Metric Tons)	646.3	176.3
Change from 1990 (Percent)	13.1%	13.1%
Average Annual Increase, 1990-1999 (Percent)	1.4%	1.4%

Total emissions of carbon dioxide in the United States and its territories in 1999 are estimated at 1,526.8 million metric tons carbon equivalent—19.4 million metric tons carbon equivalent (1.3 percent) more than in 1998 (Table 4). The growth in emissions in 1999 is more typical of the average annual growth rate during the 1990s (1.4 percent) than was the 0.1-percent growth in 1998 (Figure 1).

In the United States, most carbon dioxide (98 percent) is emitted as the result of the combustion of fossil fuels; consequently, carbon dioxide emissions and energy use are highly correlated. Historically, economic growth, the weather, the carbon intensity and energy intensity of the economy, and movements in energy prices have caused year-to-year fluctuations in energy consumption and resulting carbon dioxide emissions. A preliminary analysis, detailed later in this chapter, indicates that total carbon dioxide emissions in 1999 could have been higher—by as much as 29 million metric tons carbon equivalent—if weather patterns had been normal and if electricity generation from non-fossil fuels had not been unusually high (see box on page 14).

On a sectoral level, residential and commercial energy consumption is dominated by electricity use for air conditioning and fuel use for winter heating. The United States, as in 1998, again experienced warmer-than-

Figure 1. Annual Change in U.S. Carbon Dioxide Emissions, 1990-1999



Source: Estimates presented in this chapter.

normal winter and summer weather in 1999, with heating degree-days 6.4 percent below normal and cooling degree-days 3.5 percent above normal. Below-normal heating degree-days reduce the demand for fuel used for space heating, and above-normal cooling degree-days increase the demand for air conditioning. In terms of energy demand, however, heating degree-days outweigh cooling degree-days. Thus, the warmer winter more than offset the warmer summer. In part due to these deviations from normal weather, residential emissions of carbon dioxide rose by only 0.4 percent (from 288.8 million metric tons carbon equivalent in 1998 to 290.1 million metric tons carbon equivalent in 1999), while commercial sector emissions fell by 0.4 percent (from 244.5 million metric tons carbon equivalent in 1998 to 243.5 million metric tons carbon equivalent in 1999).

Industrial energy consumption, particularly in the manufacturing sector, is much less affected by the weather and more strongly affected by economic fluctuations than is energy consumption in the residential and commercial sectors. In 1999, carbon dioxide emissions from industrial energy use increased by only 0.2 percent, from 480.2 million metric tons carbon equivalent in 1998 to 481.2 million metric tons carbon equivalent in 1999. The underlying cause of the relatively small growth in industrial carbon dioxide emissions is not entirely clear, particularly in view of the 3.6-percent increase in industrial production in 1999. The six most energy-intensive industries—paper; chemicals; stone, clay and

U.S. Carbon Dioxide Emissions in 1999: Effects of Weather and High Levels of Nuclear and Hydroelectric Power Generation

A preliminary analysis by EIA indicates that U.S. energy-related carbon dioxide emissions in 1999 could have been higher by as much as 29 million metric tons carbon equivalent if weather patterns had been normal, and if electricity generation from nuclear and hydroelectric power plants had not been higher than normal.^a As in 1998, weather played a key role in moderating energy-related carbon dioxide emissions in 1999. A warmer-than-average winter for the United States as a whole meant less consumption of heating fuels. And, although the warmer-than-average weather continued throughout the summer months, demand for air conditioning in 1999 still was lower than in 1998, when the summer months were even hotter.

Analysis of the underlying weather trends indicates that in 1999 the warm winter (heating degree-days 6.4 percent below normal) meant that carbon dioxide emissions were lower by 14.7 million metric tons carbon equivalent than they would have been with normal winter weather. The warm summer (cooling degree-days 3.5 percent above normal), on the other hand, added about 3.1 million metric tons carbon equivalent above the level expected with normal summer weather. The net effect of the deviations from normal weather was that carbon emissions were lower by 11.6 million metric tons carbon equivalent than they would have been if weather patterns had been normal in 1999.

^aThe analysis described here is based on data contained in Energy Information Administration, *Short-Term Energy Outlook*, DOE/EIA-0202(2000/1S) (Washington, DC, April 2000). Energy data used elsewhere in this report are from more recent sources and, therefore, may differ from the data cited here.

Electricity generation from U.S. nuclear power plants reached an all-time high of 725.0 billion kilowatthours in 1999. Although it is difficult to define an “average” or “typical” year for nuclear power generation in the United States, the average for 1997, 1998, and 1999 was about 674 billion kilowatthours, and so that value was used as the baseline for this analysis. No new nuclear facilities have come on line in recent years, but the output from existing facilities has increased. If nuclear power generation in 1999 had remained at its 3-year average level, it is estimated that carbon dioxide emissions from fossil-fired generating plants would have been higher by 11.7 million metric tons carbon equivalent.

At 293.7 billion kilowatthours, hydroelectric power generation in 1999, while down from its high of 337.2 billion kilowatthours in 1997, still was about 8.6 percent above what would have been expected in a year of average precipitation levels. If hydroelectric power generation in 1999 had been at the average level, carbon dioxide emissions from fossil-fired generating plants would have been higher by 5.2 million metric tons carbon equivalent. Total generation from nuclear and hydroelectric power plants in 1999 was about 1,018.7 billion kilowatthours, accounting for 32.0 percent of electric utility generation. By comparison, their combined total in 1990 was 856.8 billion kilowatthours, or 30.5 percent of electric utility generation, and in 1998 it was 978.1 billion kilowatthours or 30.4 percent of the total generation by electric utilities.

glass; primary metals; petroleum products; and food—together account for approximately two-thirds of total industrial energy-related carbon dioxide emissions. In 1999, two of those six industries grew by less than 1 percent (food by 0.7 percent and primary metals by 0.8 percent); two grew by slightly more than 1 percent (paper by 1.1 percent and petroleum by 1.3 percent); and only two grew by more than 2 percent (chemicals by 2.1 percent and stone, clay and glass by 2.9 percent). Output from the less energy-intensive industries grew rapidly (e.g., computer equipment by 57.2 percent and semiconductors and related components by 47.4 percent). Because the less energy-intensive industries use relatively little energy to produce goods, even large increases in their output are associated with only minor increases in energy consumption and related carbon dioxide emissions.

Transportation sector energy demand is largely driven by income growth, fuel prices, and fuel economy trends. Propelled by gross domestic product (GDP) growth of 4.1 percent in 1999 and real disposable income growth of 3.2 percent, transportation energy-related carbon dioxide emissions increased by 2.9 percent, from 481.9 million metric tons carbon equivalent in 1998 to 496.1 million metric tons carbon equivalent in 1999. The increase in emissions accompanied large percentage increases in consumption of distillate fuel, aviation fuel, and motor gasoline.

Although net generation of electricity increased by 2.0 percent in 1999, total carbon dioxide emissions from the electric power sector increased by only 1.0 percent, from 608.5 million metric tons carbon equivalent in 1998 to 614.3 million metric tons carbon equivalent in 1999. The

growth rate in emissions was less than the growth rate in net generation in part because 54.5 billion kilowatthours of the net increase (73.2 billion kilowatthours) came from nuclear power plants, which produce essentially no carbon dioxide emissions. Nuclear electricity generation was 8.1 percent higher in 1999 than in 1998.

Nonfuel uses of fossil fuels, principally petroleum, sequestered 89.8 million metric tons carbon equivalent in 1999—4.8 million metric tons carbon equivalent (5.7 percent) more than in 1998. The major fossil fuel products that sequester carbon include liquefied petroleum gas (LPG), feedstocks for plastics and other petrochemicals, and asphalt and road oils. It is estimated that, of the amount of carbon sequestered in the form of plastic, about 3.5 million metric tons carbon equivalent was emitted as carbon dioxide from the burning of plastic components in municipal solid waste.

Emissions of carbon dioxide from non-energy-consuming industrial processes contributed 0.6 million metric tons carbon equivalent to the 1999 increase in emissions (Table 4). Emissions from cement production processes (excluding the energy portion) rose from 10.7 to 10.9 million metric tons carbon equivalent, while emissions from natural gas flaring rose from 3.9 to 4.2 million metric tons carbon equivalent.

Energy Consumption

The consumption of energy in the form of fossil fuel combustion is the largest single contributor to greenhouse gas emissions in the United States and the world. Of total 1999 U.S. carbon dioxide emissions, 98 percent, or 1,510.8 million metric tons carbon equivalent, resulted from the combustion of fossil fuels. This figure represents an increase of 1 percentage point over 1998 levels. In the short term, year-to-year changes in energy consumption and carbon dioxide emissions tend to be dominated by weather, economic fluctuations, and movements in energy prices. Over longer time spans, changes in energy consumption and emissions are influenced by other factors such as population shifts and energy consumers' choice of fuels, appliances, and capital equipment (e.g., vehicles, aircraft, and industrial plant and equipment). The energy-consuming capital stock of the United States—cars and trucks, airplanes, heating and cooling plants in homes and businesses,

steel mills, aluminum smelters, cement plants, and petroleum refineries—change slowly from one year to the next, because capital stock is retired only as it begins to break down or becomes obsolete.

The Energy Information Administration (EIA) divides energy consumption into four general sectoral categories: residential, commercial, industrial, and transportation.²⁰ Emissions from electric utilities, which provide electricity to the end-use sectors, are allocated in proportion to the electricity consumed in each sector (Table 5). Emissions from independent power producers and industrial cogenerators are included in the industrial sector estimates. EIA is in the process of moving the data on electricity generated in the industrial sector into a combined electric power sector that includes electric utilities, nonutility generators, and industrial cogenerators. When that process is completed, this report will follow the same protocol. In the interim, this report provides, below, a separate preliminary estimate of emissions from the entire electric power sector for the 1990 to 1999 time period.²¹

Residential Sector

At 290.1 million metric tons carbon equivalent, residential carbon dioxide emissions represented 19 percent of U.S. energy-related carbon dioxide emissions in 1999. The residential sector's pro-rated share of electric utility emissions accounted for about two-thirds of that

Energy End-Use Sector Sources of U.S. Carbon Dioxide Emissions, 1990-1999

Sector	Million Metric Tons Carbon Equivalent		Percent Change	
	1990	1999	1990-1999	1998-1999
Transportation	431.8	496.1	14.9%	2.9%
Industrial	454.8	481.2	5.8%	0.2%
Commercial	207.7	243.5	17.2%	-0.4%
Residential	254.2	290.1	14.1%	0.4%

Note: Electric utility emissions are distributed across sectors.

²⁰Energy consumption (and greenhouse gas emissions) estimates by end-use sector are less reliable than aggregate estimates, because in many cases EIA survey respondents attribute consumption to a particular economic sector by reference to the tariff or tax status of the buyer rather than definite knowledge of the buyer's activities. For example, a shopping mall that consumes enough electricity to be granted an "industrial" electricity tariff may be categorized as an industrial rather than a commercial customer.

²¹Because most EIA data sources include thermal energy from industrial cogenerators in estimates of nonutility carbon dioxide emissions, the estimates in this report do not agree with other EIA publications (see for example Table 12.7 of the *Annual Energy Review 1999*). In Table 10 of this report, the emissions attributable to thermal energy consumption have been estimated and removed from the emissions of nonutility generators in order to isolate emissions related only to electricity generation. The estimates for the electricity component for nonutility power producers should be considered preliminary for all years.

amount (193.4 million metric tons carbon equivalent).²² Since 1990, residential electricity-related emissions have grown by 1.9 percent annually. In contrast, emissions from the direct combustion of fuels (primarily natural gas) have increased by 0.7 percent per year, to 96.7 million metric tons carbon equivalent.

Total carbon dioxide emissions from the residential sector increased by 0.4 percent in 1999 (Table 6). Year-to-year, residential sector emissions are heavily influenced by weather. For example, in 1996, a relatively cold year, carbon dioxide emissions from the residential sector grew by 5.9 percent over 1995. In 1997, they declined by 0.4 percent due to warmer weather.

Since 1990, growth in carbon dioxide emissions attributable to the residential sector has averaged 1.5 percent per year. As a result, residential sector emissions in 1999 were 35.9 million metric tons carbon equivalent higher than in 1990, representing 22 percent of the total increase in U.S. energy-related carbon dioxide emissions since 1990. Long-term trends in residential carbon dioxide emissions are heavily influenced by demographic factors, living space attributes, and building shell and appliance efficiency choices. For example, the movement of populations into the Sunbelt tends to increase summer air conditioning consumption and promote the use of electric heat pumps, which increases indirect emissions from electricity use. Growth in the number of households, resulting from increasing population and immigration, contributes to more residential energy consumption.

Commercial Sector

Commercial sector carbon dioxide emissions, at 243.5 million metric tons carbon equivalent, account for about 16 percent of total energy-related carbon dioxide emissions, of which almost three-quarters (182.6 million metric tons carbon equivalent) is the sector's pro-rated share of electric utility emissions. Although commercial sector emissions largely have their origin in the space heating and cooling requirements of structures such as office buildings, lighting is a more important component of commercial energy demand than it is in the residential sector. Thus, although commercial sector emissions are strongly affected by the weather, they are affected less than residential sector emissions. In the longer run, because commercial activity is a factor of the larger economy, emissions from the commercial sector are more affected by economic trends and less affected by population growth than are emissions from the residential sector.

Emissions attributable to the commercial sector's pro-rated share of electricity consumption declined by 1.4 percent in 1999, while emissions from the direct combustion of fuels (dominated by natural gas, as in the residential sector) increased by 2.6 percent. Overall, carbon dioxide emissions related to commercial sector activity declined by 0.4 percent—from 244.5 to 243.5 million metric tons carbon equivalent—between 1998 and 1999 (Table 7), as the reduction in electricity-related emissions outweighed the increase in emissions from the direct combustion of fuels. Since 1990, commercial emissions growth has averaged 1.8 percent per year—the largest growth of any energy-use sector—and commercial sector carbon dioxide emissions have risen by a total of 35.8 million metric tons carbon equivalent, or 22 percent of the total increase in U.S. energy-related carbon dioxide emissions.

Transportation Sector

Transportation sector emissions, at 496.1 million metric tons carbon equivalent, accounted for one-third of total energy-related carbon dioxide emissions in 1999. Almost all (98 percent) of transportation sector emissions result from the consumption of petroleum products, particularly, motor gasoline (60 percent of transportation sector emissions), diesel fuel or "middle distillates" (20 percent), jet fuel (13 percent), and residual oil or heavy fuel oil, largely for maritime use (4 percent). Motor gasoline is used primarily in automobiles and light trucks, and middle distillates are used in heavy trucks, locomotives, and ships.

Emissions attributable to the transportation sector grew by 2.9 percent, from 481.9 million metric tons carbon equivalent in 1998 to 496.1 million metric tons carbon equivalent in 1999 (Table 8). Fuel-use patterns and related emissions sources in the transportation sector are different from those in the other energy-use sectors. By far the largest single source of emissions, motor gasoline, at 299.1 million metric tons carbon equivalent, grew by 2.1 percent. The highest rates of growth were for jet fuel emissions (which grew by 3.1 percent, from 64.2 to 66.3 million metric tons carbon equivalent) and distillate fuel emissions (which grew by 3.8 percent, from 96.4 to 100.1 million metric tons carbon equivalent). Of the total growth in U.S. energy-related carbon dioxide emissions in 1999, 91.9 percent (14.2 million metric tons carbon equivalent) was accounted for by the transportation sector. Since 1990, carbon dioxide emissions attributable to energy use in the transportation sector have grown annually at a rate of 1.6 percent, increasing by a total of 64.3 million metric tons carbon equivalent and

²² Sectoral (residential, commercial, and industrial) carbon dioxide emissions are based on the share of total electric power sector carbon dioxide emissions that can be attributed to each sector. The shares are based on the percentage of total electric utility sales purchased by each sector. All nonutility carbon dioxide emissions are allocated to the industrial sector.

representing 39.6 percent of the growth in energy-related carbon dioxide emissions from all sectors.

Industrial Sector

Industrial sector emissions, at 481.2 million metric tons carbon equivalent, accounted for about 32 percent of total U.S. energy-related carbon dioxide emissions in 1999. In terms of fuel shares, electricity purchased from electric utilities was responsible for 37.3 percent of total industrial sector emissions (179.5 million metric tons carbon equivalent), natural gas for 29.4 percent (141.6 million metric tons carbon equivalent), petroleum for 21.7 percent (104.2 million metric tons carbon equivalent), and coal for 11.3 percent (54.5 million metric tons carbon equivalent). Generally, industrial sector emissions are strongly affected by the growth of the economy.

Estimated carbon dioxide emissions related to energy consumption in the industrial sector increased by only 0.2 percent in 1999—from 480.2 to 481.2 million metric tons carbon equivalent (Table 9)—despite GDP growth of 4.1 percent. Since 1990, growth in carbon dioxide emissions attributable to industrial sector energy consumption has averaged 0.6 percent per year. As a result, total energy-related industrial emissions in 1999 were 5.8 percent (26.3 million metric tons carbon equivalent) higher than they were in 1990, despite a much larger economy. The increase in industrial sector emissions from 1990 to 1999 represents 16.2 percent of the total growth in U.S. energy-related carbon dioxide emissions.

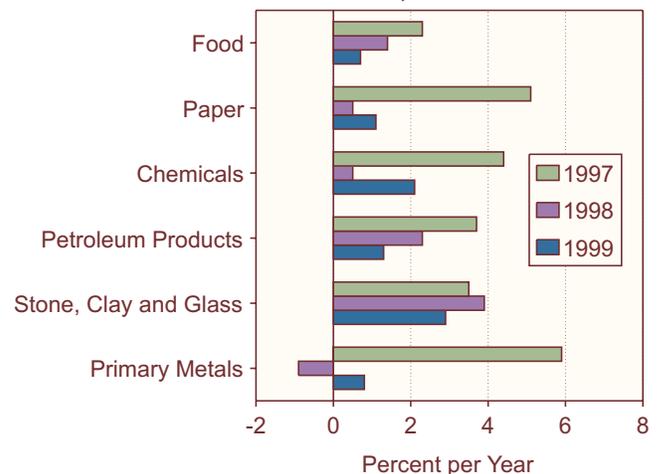
In 1999 the six most energy-intensive industry groups, which together account for approximately two-thirds of total industrial energy-related carbon dioxide emissions, grew less rapidly than the overall economy (4.1 percent) or the manufacturing component of industrial production (4.3 percent). The 1999 growth rates for the six energy-intensive industries (Figure 2) were 0.8 percent (primary metals), 2.1 percent (chemicals), 1.1 percent (paper), 2.9 percent (stone, clay and glass), 1.3 percent (petroleum), and 0.7 percent (food).²³ Thus, all the energy-intensive industries grew less rapidly than the economy as a whole. The box on page 18 discusses the importance of the energy-intensive industries to overall emissions, using data from EIA's 1994 Manufacturing Energy Consumption Survey (MECS). A new survey of manufacturers was conducted by EIA in 1998, but the results are not yet available.

What makes the low growth in industrial sector emissions even more remarkable is that this sector includes emissions from independent (nonutility) power producers and industrial cogenerators, which provide electrical

energy to the grid that is consumed in other sectors of the economy. Thus, the inclusion of carbon dioxide emissions resulting from the generation of electricity by independent power producers tends to overstate the amount of carbon dioxide attributable to the industrial sector, implying that actual emissions growth related to electrical and thermal energy use in the industrial sector may be lower than estimated here.

A contributing factor to the low growth in industrial sector carbon dioxide emissions is the erosion of the older energy-intensive (and specifically coal-intensive) industrial base. For example, coke plants consumed 38.9 million short tons of coal in 1990 but only 27.9 million short tons in 1999. Additionally, other industrial coal consumption has declined from 76.3 million short tons in 1990 to 68.0 million short tons in 1999. As a result, carbon dioxide emissions attributable to industrial coal use have declined by 13.9 million metric tons carbon equivalent or about 20 percent since 1990, helping to offset an increase of 23.3 million metric tons carbon equivalent in natural-gas-related carbon dioxide emissions (also about 20 percent) over the same time period. Because natural gas is more than 40 percent less carbon-intensive than coal, the substitution of natural-gas-fired output for coal-fired output has further contributed to the modest growth in industrial emissions. Declines in residual and distillate fuel use have resulted in an additional decrease in emissions of 5 million metric tons carbon equivalent between 1990 and 1999.

Figure 2. Energy-Intensive Industrial Production Annual Growth Rates, 1997-1999



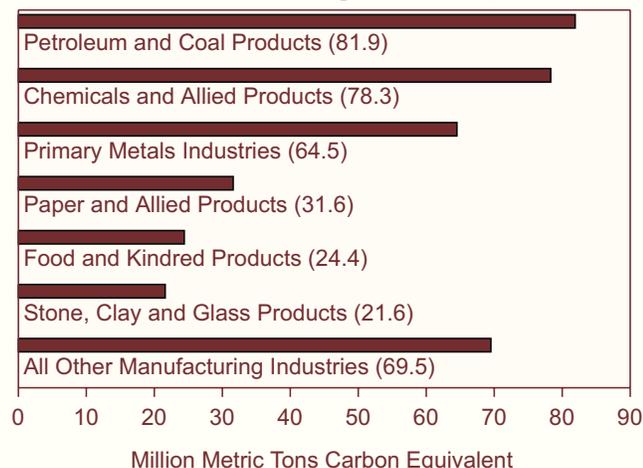
Sources: U.S. Federal Reserve Board, "G17 Historical Data: Industrial Production and Capacity Utilization," web site www.federalreserve.gov/release/G17/download.htm.

²³U.S. Federal Reserve Board, "G17 Historical Data: Industrial Production and Capacity Utilization," web site www.federalreserve.gov/release/G17/download.htm.

Energy-Related Carbon Dioxide Emissions in Manufacturing

Manufacturing, which accounts for 80 percent of industrial energy consumption, also accounts for 80 percent of industrial energy-related carbon emissions. In 1994, two industries, petroleum and chemicals, emitted over 40 percent of the energy-related carbon in manufacturing. The next four largest emitters (primary metals, paper, food, and the stone, glass, and clay products industry) produced the other 40 percent of the energy-related carbon emissions from manufacturing (see figure).

Total Energy-Related Carbon Dioxide Emissions for Selected Manufacturing Industries, 1994



Source: Energy Information Administration, Form EIA-846, "1994 Manufacturing Energy Consumption Survey," and Form EIA-810, "Monthly Refinery Report" (1994).

The carbon intensity of energy use is the amount of carbon emitted per unit of energy used. Both the mix of energy sources used and the uses of energy affect carbon intensity. Overall, manufacturing industries had a carbon intensity of 17.16 million metric tons per quadrillion Btu in 1994; however, the carbon intensities of the various industries differed markedly.

³Appendixes for this report are available on web site www.eia.doe.gov/oiaf/1605/ggrrpt/index.html.

The petroleum industry and the chemical industry both convert energy sources into products, such as petrochemical feedstocks and plastics. Only part of the carbon content is emitted to the atmosphere, the rest being sequestered in the product (see Table A2 in Appendix A).^a As a result of the nonfuel use of energy sources, the petroleum and chemical industries had lower than average carbon intensities in 1994, 12.91 and 14.69 million metric tons per quadrillion Btu, respectively.

The paper industry uses wood byproducts extensively, yielding a carbon intensity of 11.87 million metric tons per quadrillion Btu in 1994. The carbon emissions from wood combustion are considered to be zero, because the carbon emitted has been recently sequestered and the regrowing of the trees will re-sequester the emitted carbon. In contrast, the primary metals industry, which relies heavily on carbon-intensive coal and, to a lesser extent, on electricity (much of which is generated using coal), had an overall carbon intensity of 26.19 million metric tons per quadrillion Btu in 1994.

The food industry and the stone, metal, and glass industry both had carbon intensities that were slightly above the average for all manufacturing industries. However, the carbon intensities for these two industries, and for the primary metals industry, were comparable to those for "All Other Manufacturing Industries" (25.45 million metric tons per quadrillion Btu).

Electricity use is the main source of carbon dioxide emissions in industries outside the top six emitters. Other manufacturing includes industries such as textile mill products, furniture and fixtures, leather and leather products, fabricated metal products, industrial machinery, and electric and electronic products. Their collective carbon intensity was 25.45 million metric tons per quadrillion Btu in 1994.

Electric Power Industry

In the data presented by sector above, carbon dioxide emissions from electric utility fuel use are assigned to the energy-consuming sectors. However, because the electric power industry is changing and the "electric utility" designation is becoming less relevant, this section and the data in Table 10 present an estimate of carbon dioxide emissions for the entire electric power

industry. By this accounting, emissions from the electric power industry as a whole made up 41 percent of total U.S. energy-related carbon dioxide emissions in 1999.

Carbon dioxide emissions from the electric power industry, despite a strong economy, increased by only 1.0 percent, from 608.5 million metric tons carbon equivalent in 1998 to 614.3 million metric tons carbon equivalent in 1999 (Table 10).²⁴ Although 1999 was

²⁴The emissions estimates given are for both electric utility and nonutility power producers. No attempt has been made, however, to subtract nonutility emissions from the industrial sector by fuel. Therefore, the estimate should be considered separately from the preceding emissions estimates by sector. A report produced by the U.S. Department of Energy and the U.S. Environmental Protection Agency, *Carbon Dioxide Emissions from the Generation of Electric Power in the United States* (Washington, DC, July 2000), used more preliminary data and a different methodology, resulting in an estimated emissions growth rate of 1.4 percent from 1998 to 1999.

Electric Power Industry Carbon Dioxide Emissions by Fuel Input, 1990-1999

Fuel	Million Metric Tons Carbon Equivalent		Percent Change	
	1990	1999	1990-1999	1998-1999
Petroleum	28.2	27.2	-3.8%	-2.7%
Natural Gas	60.9	87.3	43.4%	2.4%
Coal	420.6	498.8	18.6%	0.9%
Total	509.6	614.3	20.5%	1.0%

warmer than average, the summer of 1998 was even warmer than the summer of 1999, thus, demand for electric power was dampened by the decline in cooling degree-days from 1998 to 1999. Since 1990, electric power industry carbon dioxide emissions have grown by 20.5 percent, while total carbon dioxide emissions have grown by 12.0 percent.

Electric utility carbon dioxide emissions have increased by 12 percent, from 479.5 million metric tons carbon equivalent in 1990 to 532.7 million metric tons carbon equivalent in 1999. Increases in the shares of generation from nuclear and hydroelectric power plants have kept the growth in emissions lower than would have been the case had more of the growth been in fossil-fuel-powered generation (see box on page 14).

Carbon dioxide emissions attributable to nonutility power producers have risen by 171 percent, from 30.1 million metric tons carbon equivalent in 1990 to 81.6 million metric tons carbon equivalent in 1999. Over that time period the nonutility power sector has grown by 139 percent, from 216.7 billion kilowatthours of generation in 1990 to 517.4 billion kilowatthours in 1999. One of the factors that has increased the carbon intensity of nonutility power producers is their increased reliance on coal. In 1990, only 14 percent of nonutility generation was coal-powered. By 1999, coal's share had risen to 22 percent.²⁵ As the industry has been deregulated, some of the coal-fired generation facilities formerly operated by electric utilities have been divested and are now being operated by nonutility power producers.

Nonfuel Use of Energy Inputs

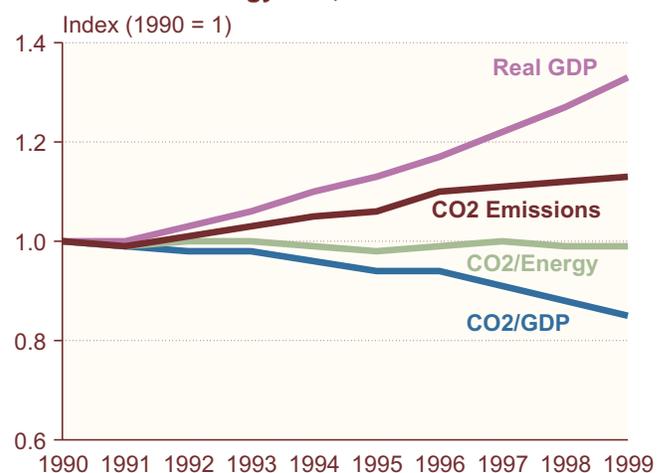
In 1999, 89.8 million metric tons carbon equivalent was sequestered through nonfuel uses of fossil fuels (Table 11). A small amount of this was coal-based (less than 0.5 million metric tons carbon equivalent), about 5.3 million

metric tons carbon equivalent was natural-gas-based, and the remainder (84.1 million metric tons carbon equivalent) was petroleum-based. The products that sequester carbon include feedstocks for plastics and other petrochemicals, asphalt and road oil, liquefied petroleum gas, lubricants, and waxes. The amount sequestered in 1999 was 5.7 percent higher than in 1998, when 85.0 million metric tons carbon equivalent was sequestered. Since 1990 sequestration of carbon in this manner has increased by 21.1 million metric tons carbon equivalent or 30.7 percent, translating to an annual average growth rate of 3 percent, or more than twice the rate of growth in carbon dioxide emissions.

Carbon Dioxide Emissions and Economic Growth

The relationship between economic growth and growth in energy-related carbon dioxide emissions is important in understanding both past emissions growth and what may be the trend in future emissions. Figure 3 shows U.S. carbon dioxide and GDP growth during the 1990s indexed to 1990. The United States experienced a period of prosperity during the 1990s, with economic growth averaging 3.1 percent per year. Carbon dioxide emissions, however, grew by an average of only 1.4 percent annually. As a result, the carbon dioxide intensity of U.S. GDP (carbon dioxide emissions divided by GDP)

Figure 3. Growth in U.S. Carbon Dioxide Emissions and Gross Domestic Product and Carbon Dioxide Intensities of GDP and Energy Use, 1990-1999



Sources: Energy Information Administration, *Annual Energy Review 1999*, DOE/EIA-0384(99) (Washington, DC, July 2000), Tables 1.1 and E1; and estimates presented in this chapter.

²⁵With carbon dioxide emissions from nonutility generators increasing by 171 percent and electricity output increasing by 139 percent, carbon intensity has increased by 24 percent.

actually declined by 1.7 percent per year, and in 1999 was 14.3 percent lower than it was in 1990.

In order to analyze trends in the carbon dioxide intensity of GDP, it is important to evaluate both the energy intensity of GDP (energy consumed per dollar of GDP) and the carbon dioxide intensity of energy use (carbon-equivalent emissions per unit of energy consumed). When the economy grows faster than carbon dioxide emissions, as in the 1990s, it means that either the energy/GDP intensity, the carbon/energy intensity, or both have declined, causing a divergence between the growth rates for GDP and carbon dioxide emissions.

In examining 1990 to 1999 growth rates, it is clear that the primary cause of the divergence between the growth rates for GDP and carbon dioxide emissions is a decline in the energy intensity of the economy, which has fallen by an average of 1.5 percent per year since 1990. In comparison, the carbon intensity of U.S. energy use has declined by an average of only 0.2 percent per year during the 1990s. Thus, it is primarily the use of less energy per unit of economic output, not the use of low-carbon fuels, that has kept the rate of carbon dioxide emissions growth below the GDP growth rate.

The decrease in the energy intensity of the U.S. economy has resulted, in part, from an increase in the non-energy-intensive sectors of the economy relative to the traditional energy-intensive manufacturing industries, as well as energy efficiency improvements. For example, the robust economic growth in 1999 occurred for the most part in industries that are less energy-intensive than the traditional basic industries: for example, computer equipment manufacturing grew by 51 percent, and the manufacture of semiconductors and related components grew by 44 percent in 1999. Such growth in the so-called “new economy” means that less energy is used and less carbon dioxide is emitted per dollar of GDP. The production of computer software requires very little energy consumption in comparison with industrial processes such as steelmaking.

As long as U.S. economic growth continues to be led by industries that use relatively little energy per unit of output, it will have little *direct* effect on energy consumption and related carbon dioxide emissions. Economic growth of this kind does, however, have an *indirect* effect on emissions as people with more disposable income use more energy services (such as travel) and tend to live in larger houses. On the other hand, such income effects can be offset somewhat by more energy-efficient vehicles, building shells, appliances, and heating and cooling equipment.

²⁶Military bunker fuels decreased steadily from 1990 (4.9 million metric tons carbon equivalent) to 1994, where they appear to have stabilized at 2.5 ± 0.2 million metric tons carbon equivalent.

Adjustments to Energy Consumption

Total energy consumption and the carbon emissions upon which they are based correspond to EIA’s coverage of energy consumption, which includes the geographic area of the United States defined as the 50 States and the District of Columbia. Under international protocol, however, the United States is also responsible for emissions emanating from its territories, and their emissions are added to the U.S. total. Conversely, because the Intergovernmental Panel on Climate Change (IPCC) definition of energy consumption excludes international bunker fuels from the statistics of all countries, emissions from international bunker fuels are subtracted from the U.S. total. Additionally, beginning with this year’s report, military bunker fuels have been subtracted because they are also excluded by the IPCC from the national total. These sources and subtractions are enumerated and described as “adjustments to energy.”

U.S. Territories

Energy-related carbon dioxide emissions for the U.S. territories are added as an adjustment in keeping with IPCC guidelines for national emissions inventories. The territories included are Puerto Rico, the U.S. Virgin Islands, American Samoa, Guam, the U.S. Pacific Islands, and Wake Island. Most of these emissions are from petroleum products; however, Puerto Rico and the Virgin Islands consume coal in addition to petroleum products. For 1999, total carbon dioxide emissions from the U.S. Territories are estimated at 13.5 million metric tons carbon equivalent (Table 4).

International Bunker Fuels

In keeping with the IPCC guidelines for estimating national greenhouse gas emissions, carbon dioxide emissions from international bunker fuels are subtracted from the estimate of total U.S. energy-related emissions of carbon dioxide. The estimate for bunker fuels is based on purchases of distillate and residual fuels by foreign-bound ships at U.S. seaports, as well as jet fuel purchases by international air carriers at U.S. airports. Additionally, U.S. military operations that consume fuel originally purchased in the United States are subtracted from the total, because they are also considered international bunker fuels under this definition.

For 1998, the most recent year for which data are available, the emissions estimate for bunker fuels is 2.7 million metric tons carbon equivalent.²⁶ In 1999, it is

Analysis of Uncertainty in Energy-Related Carbon Dioxide Emissions

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, as established at the December 1997 Kyoto meetings, recommend that nations carry out analyses to estimate the uncertainty in their national carbon emissions inventories. According to the guidelines, nations should construct 95 percent confidence intervals for their carbon emissions using classical sampling techniques, Monte Carlo techniques, or assessments by national experts.

In response to the good practices guidelines, EIA in 1998 used a "Tier I" approach, calculating a weighted uncertainty as the square root of the sum of the squared activity factor and emissions factor errors multiplied by the point estimate of the share of total emissions for the source. This was done for carbon dioxide, methane, nitrous oxide, and other gases. The Tier I approach, however, may be inappropriate when combining non-normal distributions, as may be some of the distributions for emissions factors and activities.

EIA has recently begun a "Tier II" uncertainty analysis of the energy-related carbon dioxide emissions estimate to augment its previous "Tier I" uncertainty analysis. Preliminary results from the "Tier II" analysis are presented here. Details of the "Tier I" analysis for all gases are available in Appendix C.^a

The Tier II uncertainty analysis involves Monte Carlo simulations that facilitate the combination of various

types of probability density functions. Through repeated iterations, points inside the relevant probability density functions for both the activity data and the emissions factors for energy-related carbon dioxide emissions are sampled. The other gases, methane and nitrous oxides, will also be subject to a similar "Tier II" analysis by the U.S. Environmental Protection Agency.

The table below shows the estimated bias and random uncertainties in EIA's activity data and emissions factors for petroleum, coal, and natural gas. For petroleum, the activity data are divided into the following sectors: residential, commercial, and transportation (R,C,T); industrial; electric utility; and nonfuel use. For coal, the division is between electric utility and "other sectors" (industrial combined with residential, commercial, and transportation). For natural gas the division is the same as for coal, plus flared.

Because the underlying data are obtained from various EIA surveys, they have different levels of associated uncertainty. For example, the maximum bias error for coal activity associated with electric utilities is estimated to be 4 percent, whereas the maximum bias error for coal activity associated with the "Other Sectors" is estimated to be 7 percent. This is because fuel use among the reporting electric utilities is well known, but for the other sectors (especially residential and commercial) the data are less reliable.

(continued on page 22)

Bias and Random Uncertainties Associated with EIA Reported Data, 1999

Source	Activity Data			Emissions Factors		
	Bias		Random	Bias		Random
	Minimum	Maximum		Minimum	Maximum	
Petroleum						
R,C,T	2.0%	2.5%	0.5%	1.0%	1.0%	0.5%
Industrial (Gross)	2.0%	3.0%	0.6%	4.0%	4.0%	0.6%
Electric Utility	0.5%	2.0%	0.5%	3.0%	3.0%	0.6%
Nonfuel Use	1.0%	4.0%	0.6%	3.0%	3.0%	0.6%
Coal						
Electric Utility	0.5%	4.0%	0.6%	1.0%	1.0%	0.5%
Other Sectors.	1.0%	7.0%	0.7%	1.0%	1.0%	0.5%
Natural Gas						
Electric Utility	0.5%	2.0%	0.5%	0.0%	0.0%	0.4%
Flared.	10.0%	20.0%	2.0%	10.0%	10.0%	5.0%
Other Sectors.	0.5%	3.0%	0.5%	0.0%	0.0%	0.4%

R,C,T = residential, commercial, and transportation.

Notes: Bias errors account for the variability of data due to various factors. Random errors are "real" uncertainties resulting from either measurement or filing errors.

Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999), and EIA expert judgment.

^aAppendixes for this report are available on web site www.eia.doe.gov/oiaf/1605/ggprt/index.html.

Analysis of Uncertainty in Energy-Related Carbon Dioxide Emissions (Continued)

The first table below gives the “Tier II” simulated energy-related carbon dioxide emissions (which are very close to the estimated values), and the second table below gives estimates of the expected ranges, or uncertainty bands, around the estimates of carbon dioxide emissions at the 90-percent confidence level. The expected uncertainty ranges around each energy

source category, however, are not additive. The second table indicates that the total uncertainty around the simulated mean value of 1,527 million metric tons carbon equivalent for 1999 energy-related carbon dioxide emissions is 83 million metric tons carbon equivalent, or 5.5 percent (-2.7 percent and +2.8 percent).

Simulated U.S. Carbon Dioxide Emissions from Energy Use, 1990-1999
(Million Metric Tons Carbon Equivalent)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Petroleum										
R,C,T	476.0	461.0	461.4	476.4	477.8	500.2	511.1	495.4	504.3	532.3
Industrial (Gross)	80.6	64.4	85.7	76.2	84.2	71.2	82.8	87.2	76.7	82.9
Electric Utility	27.0	24.8	19.8	22.2	21.0	14.2	15.2	17.6	24.2	20.3
Nonfuel Use.	18.9	16.9	19.5	19.4	19.3	19.4	20.4	19.7	21.8	22.9
Total Petroleum.	583.6	550.2	567.0	574.8	582.9	585.7	609.1	600.3	605.2	635.5
Coal										
Electric Utility	428.1	426.8	427.3	435.0	452.2	449.7	479.8	491.7	518.1	510.5
Other Sectors	73.3	71.7	68.0	70.1	69.5	69.2	64.5	68.6	65.6	62.5
Total Coal	501.3	498.5	495.2	505.2	521.6	518.9	544.3	560.3	583.8	573.0
Natural Gas										
Electric Utility	41.4	41.8	40.6	40.3	44.4	47.1	41.1	44.2	48.3	46.6
Flared	2.8	2.8	2.9	4.5	3.2	5.3	4.8	5.2	4.0	4.8
Other Sectors	237.1	237.1	240.8	254.5	256.2	264.6	275.6	281.8	263.5	267.5
Total Natural Gas	281.3	281.7	284.4	299.3	303.8	317.0	321.6	331.2	315.9	318.9
Total All Fuels	1,366.3	1,330.4	1,346.6	1,379.3	1,408.3	1,421.6	1,475.1	1,491.7	1,504.9	1,527.5

R,C,T = residential, commercial, and transportation.
Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999), and EIA's Greenhouse Gas Inventory Database.

Expected Error Ranges for U.S. Carbon Dioxide Emissions Estimates, 1990-1999
(Million Metric Tons Carbon Equivalent)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Petroleum										
R,C,T	43.7	48.1	48.1	47.1	47.6	48.5	54.1	51.0	49.4	54.0
Industrial (Gross)	13.4	11.1	14.0	12.2	12.8	11.7	14.0	13.5	12.1	12.8
Electric Utility	3.1	2.9	2.3	2.8	2.3	1.7	1.7	2.0	2.9	2.5
Nonfuel Use.	2.6	2.7	2.9	2.7	2.8	2.8	2.8	3.1	3.0	3.5
Total Petroleum.	47.2	52.9	53.7	52.9	51.3	53.8	55.9	52.3	56.1	54.4
Coal										
Electric Utility	42.1	43.0	46.2	46.6	45.6	48.4	48.4	47.4	53.8	52.5
Other Sectors	11.0	9.8	9.6	9.3	9.7	9.5	9.5	8.9	9.5	8.4
Total Coal	44.2	49.7	46.9	49.3	49.2	49.7	48.5	50.2	56.4	56.0
Natural Gas										
Electric Utility	2.8	2.5	2.5	2.5	2.7	2.9	2.6	2.9	3.1	3.3
Flared	1.8	2.2	1.9	2.7	3.0	3.6	3.4	3.5	3.5	3.5
Other Sectors	17.2	17.1	17.5	20.4	18.5	19.7	19.8	21.0	20.6	21.4
Total Natural Gas	17.2	18.1	18.6	21.1	18.7	20.3	21.4	21.6	21.8	21.7
Total All Fuels	79.8	76.5	78.5	78.4	74.7	80.3	81.3	80.6	81.0	82.8

R,C,T = residential, commercial, and transportation.
Notes: Values shown reflect absolute values of positive and negative ranges. For 1999, the total uncertainty range is 5.5 percent (-2.7 percent, +2.8 percent) at the 90-percent confidence interval.
Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999), and EIA's Greenhouse Gas Inventory Database.

estimated that a combined total of approximately 29.3 million metric tons carbon equivalent was emitted from international bunker fuels (26.6 million metric tons carbon equivalent) and military bunker fuels (assuming the latter was close to the 1998 estimate). This amount is subtracted from the U.S. total in Table 4. Just over half of the carbon dioxide emissions associated with international bunker fuels are attributed to the combustion of jet fuels. Emissions from marine bunker fuels, largely attributable to oil burned by ocean-going merchant ships, account for the balance of emissions from civilian bunker fuels.

Other Carbon Dioxide Emissions

Energy Production

In addition to emissions resulting from fossil energy consumed, oil and gas production leads to emissions of carbon dioxide from sources other than the combustion of those marketed fossil fuels. The two energy production sources estimated for this report are:

- Flared natural gas, which is flared either because the cost of bringing the gas to market is prohibitive or because the gas is of insufficient quality to sell
- Carbon dioxide scrubbed from natural gas to improve its heat content and quality and subsequently vented to the atmosphere.

Because many States require flaring of natural gas, EIA assumes that all gas reported under the category "Vented and Flared" is actually flared and therefore is a carbon dioxide emission rather than a methane emission. In 1999, about 4.2 million metric tons carbon equivalent was emitted in this way (Table 4).

By computing the difference between the estimated carbon dioxide content of raw gas and the carbon dioxide content of pipeline gas, the amount of carbon dioxide that has been removed (scrubbed) in order to improve the heat content and quality of natural gas can be calculated. This amount was about 4.9 million metric tons carbon equivalent in 1999 (Table 4). Appendix D describes additional energy production sources that are excluded from this report.²⁷

Industrial Process Emissions

Industrial emissions not caused by the combustion of fossil fuels accounted for only about 1.3 percent (19.2 million metric tons carbon equivalent) of total U.S.

carbon dioxide emissions in 1999 (Table 12). Process-related emissions from industrial sources depend largely on the level of activity in the construction industries and on production at oil and gas wells. These sources include limestone and dolomite calcination, soda ash manufacture and consumption, carbon dioxide manufacture, cement manufacture, and aluminum production.

Estimated industrial process emissions of carbon dioxide in 1999 were 2.8 million metric tons carbon equivalent (17.1 percent) higher than in 1990 and 0.3 million metric tons carbon equivalent (1.7 percent) higher than in 1998. Of the total carbon dioxide emissions from industrial processes, 57 percent are from cement manufacture. When calcium carbonate is heated (calcined) in a kiln, it is converted to lime and carbon dioxide. The lime is combined with other materials to produce clinker (an intermediate product from which cement is made), and the carbon dioxide is released to the atmosphere. In 1999, the United States manufactured an estimated 86.0 million metric tons of cement, resulting in the direct release of carbon dioxide containing 10.9 million metric tons carbon equivalent into the atmosphere. This calculation is independent of the carbon released by the energy consumed in making cement. This represents an increase in carbon dioxide emissions of 1.9 million metric tons carbon equivalent (20.4 percent) compared with 1990 and an increase of about 0.2 million metric tons carbon equivalent (2.1 percent) compared with 1998.

There are numerous other industrial processes in which carbonate minerals are used in ways that release carbon dioxide into the atmosphere, including the use of limestone in the production of lime and in flue gas desulfurization and the manufacture and some uses of soda ash. Carbon dioxide is also released during aluminum smelting, when carbon anodes (with the carbon derived from nonfuel use of fossil fuels) are vaporized in the presence of aluminum oxide. Approximately 8.2 million metric tons carbon equivalent was released in emissions from these other industrial process sources in 1999.

Municipal solid waste that is combusted contains, on average, a portion that is composed of plastics. The carbon in these plastics has normally been accounted for as sequestered carbon, as reported in Table 11. However, according to the IPCC, to properly account for that carbon, emissions from the plastics portion of the municipal solid waste must be counted in total national emissions inventories. These emissions produce about 3.5 million metric tons carbon equivalent. Under international agreement, the emissions are counted under the category of waste management, although most of the

²⁷Appendixes for this report are available on web site www.eia.doe.gov/oiaf/1605/ggrpt/index.html.

municipal solid waste is burned in the production of electricity. These emissions are calculated by the U.S. EPA, with the most recent estimate being for 1998. The 1998 value has been used as an estimate for 1999.²⁸

Carbon Coefficients

This year, in keeping with EIA's Strategic Plan for electronic dissemination of EIA data, the appendixes for this report are not included in the print version of the report but instead are being made available for viewing and/or download at web site www.eia.doe.gov/oiaf/1605/ggrpt/index.html. Appendix B describes the derivation of the carbon emissions coefficients used for this report. For the convenience of readers, the carbon coefficients that appear in Appendix B are repeated in Table 13.

Because motor gasoline consumption accounts for nearly 20 percent of all U.S. anthropogenic carbon

dioxide emissions, small changes in the emissions coefficient can yield relatively large changes in the overall emissions estimate. Thus, EIA revises the emissions coefficient for motor gasoline annually. As is the case for all petroleum products, the emissions coefficient for motor gasoline is a function of its density and carbon content. This relationship is particularly clear for motor gasoline, which is largely free of impurities due to the narrow range of operating conditions in modern automobile engines.

All other emissions coefficients for fossil fuels remain unchanged from previous editions of this report, with the exception of crude oil. The crude oil coefficient is not used directly in EIA estimation methods but is provided for those analysts wishing to perform a top-down calculation for comparative purposes.²⁹ More detailed discussion of variations in emissions coefficients is provided in Appendix B.

²⁸The U.S. Department of Energy and the U.S. Environmental Protection Agency jointly produce a report to the President that estimates municipal solid waste emissions of carbon dioxide. The number differs slightly from the EPA estimate used in this report. Because this report is required to cover emissions since 1990 and the Report to the President covers only the two most recent years, this report is calibrated to the EPA inventory submitted through international channels to the United Nations Framework Convention on Climate Change.

²⁹Changes in the category "other petroleum" reflect changes in the consumption weighting of the underlying fuels rather than alterations in their emissions coefficients.

Table 4. U.S. Carbon Dioxide Emissions from Energy and Industry, 1990-1999
(Million Metric Tons Carbon Equivalent)

Fuel Type or Process	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Energy Consumption										
Petroleum	590.4	576.1	586.7	587.7	600.3	596.3	618.7	624.6	634.9	649.7
Coal	484.8	481.0	486.1	502.1	507.7	510.3	532.6	547.3	550.0	549.3
Natural Gas	273.2	278.1	286.3	295.4	301.5	314.4	320.2	321.4	310.5	311.8
Geothermal	0.1	0.1	0.1	0.1	*	*	*	*	*	*
Energy Subtotal.	1,348.6	1,335.3	1,359.1	1,385.3	1,409.6	1,421.0	1,471.5	1,493.4	1,495.4	1,510.8
Adjustments to Energy										
U.S. Territories (+).	8.7	10.1	9.9	10.8	10.9	11.3	10.0	10.7	12.2	13.5
Military Bunker Fuels (-).	4.9	3.6	3.3	3.0	2.6	2.4	2.5	2.6	2.7	2.7
International Bunker Fuels (-)	27.3	29.1	26.7	24.2	24.1	25.1	25.4	27.3	28.6	26.6
Total Energy Adjustments	-23.5	-22.6	-20.1	-16.4	-15.8	-16.2	-17.9	-19.2	-19.1	-15.8
Adjusted Energy Total	1,325.0	1,312.7	1,339.0	1,368.9	1,393.7	1,404.7	1,453.6	1,474.1	1,476.3	1,495.0
Other Sources										
Gas Flaring	2.5	2.8	2.8	3.7	3.8	4.7	4.5	4.2	3.9	4.2
CO ₂ in Natural Gas	3.8	4.0	4.2	4.4	4.6	4.6	4.8	4.9	4.9	4.9
Cement Production	9.1	8.9	8.9	9.5	10.0	10.1	10.1	10.5	10.7	10.9
Other Industrial	7.3	7.2	7.2	7.1	7.2	7.6	7.9	8.0	8.1	8.2
Waste Combustion	2.8	3.0	3.0	3.1	3.1	3.0	3.1	3.4	3.5	3.5
Total Other Sources	25.5	25.8	26.1	27.9	28.7	30.0	30.4	31.0	31.1	31.7
Total	1,350.5	1,338.4	1,365.1	1,396.8	1,422.5	1,434.7	1,484.1	1,505.2	1,507.4	1,526.8

*Less than 50,000 metric tons carbon equivalent.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding. Adjusted energy total includes U.S. Territories.

Sources: EIA estimates presented in this chapter.

Table 5. U.S. Carbon Dioxide Emissions from Energy Consumption by End-Use Sector, 1990-1999
(Million Metric Tons Carbon Equivalent)

End-Use Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Residential	254.2	259.0	258.6	274.3	272.2	273.4	289.6	288.6	288.8	290.1
Commercial.	207.7	208.0	207.8	213.6	217.1	220.6	229.2	241.5	244.5	243.5
Industrial	454.8	444.1	461.6	461.0	471.0	469.2	483.8	489.7	480.2	481.2
Transportation	431.8	424.3	431.1	436.4	449.3	457.8	468.9	473.6	481.9	496.1
Total.	1,348.6	1,335.3	1,359.1	1,385.3	1,409.6	1,421.0	1,471.5	1,493.4	1,495.4	1,510.8

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding. Electric utility emissions are distributed across the end-use sectors. Nonutility power producers emissions are allocated to the industrial sector. Emissions allocated to sectors are unadjusted. Adjustments are made to total emissions only (Table 4).

Sources: EIA estimates presented in this chapter.

Carbon Dioxide Emissions

Table 6. U.S. Carbon Dioxide Emissions from Residential Sector Energy Consumption, 1990-1999
(Million Metric Tons Carbon Equivalent)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Petroleum										
Liquefied Petroleum Gas	6.3	6.7	6.6	6.8	6.8	6.9	7.5	7.5	7.2	8.1
Distillate Fuel	16.5	16.4	17.1	18.0	17.4	17.4	18.4	17.8	15.4	16.0
Kerosene	1.2	1.4	1.3	1.5	1.3	1.5	1.7	1.8	2.1	2.0
Petroleum Subtotal	24.0	24.5	24.9	26.3	25.4	25.8	27.6	27.1	24.7	26.0
Coal.	1.6	1.4	1.5	1.5	1.4	1.4	1.4	1.5	1.1	1.1
Natural Gas.	65.1	67.5	69.4	73.4	71.7	71.8	77.6	73.8	67.2	69.5
Electric Utility ^a	163.5	165.6	162.8	173.1	173.6	174.5	183.0	186.2	195.7	193.4
Total	254.2	259.0	258.6	274.3	272.2	273.4	289.6	288.6	288.8	290.1

^aShare of total electric utility carbon dioxide emissions weighted by sales to the residential sector.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 7. U.S. Carbon Dioxide Emissions from Commercial Sector Energy Consumption, 1990-1999
(Million Metric Tons Carbon Equivalent)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Petroleum										
Motor Gasoline	2.1	1.6	1.5	0.6	0.5	0.4	0.5	0.8	0.8	0.9
Liquefied Petroleum Gas	1.1	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.4
Distillate Fuel	9.6	9.5	9.2	9.2	9.2	9.1	9.4	8.8	8.3	8.6
Residual Fuel	5.0	4.5	4.1	3.7	3.7	3.1	3.0	2.4	1.9	2.2
Kerosene	0.2	0.2	0.2	0.3	0.4	0.4	0.4	0.5	0.6	0.6
Petroleum Subtotal	18.0	17.1	16.1	14.9	14.9	14.1	14.6	13.9	13.0	13.7
Coal.	2.4	2.2	2.2	2.2	2.1	2.1	2.1	2.2	1.7	1.7
Natural Gas.	38.8	40.4	41.5	42.4	42.9	44.9	46.8	47.7	44.6	45.4
Electric Utility ^a	148.5	148.3	148.0	154.1	157.2	159.5	165.7	177.7	185.2	182.6
Total	207.7	208.0	207.8	213.6	217.1	220.6	229.2	241.5	244.5	243.5

^aShare of total electric utility carbon dioxide emissions weighted by sales to the commercial sector.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 8. U.S. Carbon Dioxide Emissions from Transportation Sector Energy Consumption, 1990-1999
(Million Metric Tons Carbon Equivalent)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Petroleum										
Motor Gasoline	260.6	259.2	263.1	268.9	273.3	279.0	284.0	286.5	292.9	299.1
Liquefied Petroleum Gas	0.4	0.3	0.3	0.3	0.6	0.3	0.3	0.2	0.2	0.3
Jet Fuel	60.1	58.1	57.6	58.1	60.4	60.0	62.7	63.3	64.2	66.3
Distillate Fuel	75.7	72.6	75.3	77.3	82.5	85.1	89.7	93.5	96.4	100.1
Residual Fuel	21.9	22.0	23.0	19.4	19.1	19.7	18.4	15.5	15.2	17.5
Lubricants	1.8	1.6	1.6	1.6	1.7	1.7	1.6	1.7	1.8	1.8
Aviation Gasoline	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Petroleum Subtotal	421.2	414.6	421.6	426.4	438.2	446.5	457.4	461.5	471.5	485.8
Coal.	*	*	*	*	*	*	*	*	*	*
Natural Gas.	9.8	9.0	8.8	9.3	10.2	10.4	10.6	11.3	9.5	9.5
Electric Utility ^a	0.7	0.7	0.7	0.7	0.9	0.8	0.8	0.8	0.9	0.8
Total	431.8	424.3	431.1	436.4	449.3	457.8	468.9	473.6	481.9	496.1

*Less than 50,000 metric tons carbon equivalent.

^aShare of total electric utility carbon dioxide emissions weighted by sales to the transportation sector.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 9. U.S. Carbon Dioxide Emissions from Industrial Sector Energy Consumption, 1990-1999
(Million Metric Tons Carbon Equivalent)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Petroleum										
Motor Gasoline	3.6	3.7	3.7	3.5	3.7	3.9	3.9	4.1	3.8	3.9
Liquefied Petroleum Gas	12.0	12.1	12.7	12.1	12.9	12.7	13.7	14.0	13.3	14.9
Distillate Fuel	23.3	22.4	22.5	21.7	21.8	21.1	22.2	22.4	22.5	22.7
Residual Fuel	8.4	6.5	7.7	9.0	8.5	6.7	6.7	5.8	4.7	3.9
Asphalt and Road Oil	*	*	*	*	*	*	*	*	*	*
Lubricants	1.9	1.7	1.7	1.7	1.8	1.8	1.7	1.8	1.9	1.9
Kerosene	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4
Other Petroleum.	51.4	48.4	55.3	49.5	52.1	49.4	55.2	56.3	54.2	56.4
Petroleum Subtotal	100.7	95.0	103.9	97.7	101.2	96.0	103.8	104.7	100.9	104.2
Coal.	68.3	64.5	61.8	61.7	62.0	61.8	59.9	59.9	56.0	54.5
Coal Coke Net Imports	0.1	0.2	0.9	0.7	1.5	1.5	0.6	1.2	1.7	1.5
Natural Gas.	118.3	120.2	125.9	130.9	132.7	140.4	145.3	145.1	141.2	141.6
Electric Utility ^a	167.3	164.0	169.2	170.0	173.5	169.5	174.2	178.8	180.5	179.5
Total	454.8	444.1	461.6	461.0	471.0	469.2	483.8	489.7	480.2	481.2

*Less than 50,000 metric tons carbon equivalent.

^aShare of total electric utility carbon dioxide emissions weighted by sales to the industrial sector.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Carbon Dioxide Emissions

Table 10. U.S. Carbon Dioxide Emissions from Electricity Generation, 1990-1999
(Million Metric Tons Carbon Equivalent)

Generator Type and Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Electric Utility										
Coal	411.6	407.7	412.4	427.3	430.2	433.0	457.5	471.7	475.6	466.9
Petroleum	26.4	24.9	20.2	22.3	20.5	13.9	15.3	17.5	24.8	20.0
Natural Gas	41.5	41.1	40.7	39.5	44.0	47.2	40.3	43.6	47.9	45.8
Electric Utility Subtotal	479.5	473.7	473.2	489.1	494.6	494.1	513.1	532.8	548.3	532.7
Nonutility Power Producers^a										
Coal	9.0	11.2	13.0	14.5	16.1	16.2	16.5	15.9	18.6	31.9
Petroleum	1.8	1.9	2.7	3.3	3.8	3.8	3.8	3.9	4.2	8.2
Natural Gas	19.4	21.5	25.5	27.5	28.0	31.0	31.1	32.4	37.3	41.5
Nonutility Subtotal	30.1	34.6	41.2	45.3	47.8	51.0	51.3	52.2	60.1	81.6
Electric Power Industry										
Coal	420.6	418.9	425.3	441.8	446.2	449.2	474.0	487.6	494.3	498.8
Petroleum	28.2	26.8	22.9	25.6	24.2	17.7	19.1	21.4	27.6	27.1
Natural Gas	60.9	62.6	66.2	67.0	71.9	78.1	71.4	75.9	85.3	87.3
Electricity Generation Total	509.6	508.3	514.4	534.3	542.4	545.1	564.5	585.0	608.5	614.3
<i>Annual Percent Change</i>		-0.3%	1.2%	3.9%	1.5%	0.5%	3.6%	3.6%	4.0%	1.0%

^aEstimated by EIA.

P = preliminary data.

Notes: Nonutility power producer data are based on estimated heat rates to remove the thermal energy component from fuel use data. Estimates differ from those contained in Energy Information Administration, *Annual Energy Review 1999*, DOE/EIA-0384(99) (Washington, DC, July 2000), Table 12.7, because of the removal of the thermal energy component. Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 11. U.S. Carbon Sequestered by Nonfuel Use of Energy Fuels, 1990-1999
(Million Metric Tons Carbon Equivalent)

End Use and Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Industrial										
Petroleum										
Liquefied Petroleum Gases	16.2	18.6	18.7	18.2	20.9	21.4	22.3	22.6	21.6	24.4
Distillate Fuel	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Residual Fuel	0.5	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5
Asphalt and Road Oil	24.1	22.2	22.7	23.7	24.2	24.3	24.2	25.2	26.0	27.3
Lubricants	1.9	1.7	1.7	1.8	1.8	1.8	1.7	1.8	1.9	2.0
<i>Other (Subtotal)</i>	<i>19.7</i>	<i>19.3</i>	<i>20.5</i>	<i>22.6</i>	<i>23.3</i>	<i>23.5</i>	<i>24.1</i>	<i>25.6</i>	<i>27.5</i>	<i>28.0</i>
Pentanes Plus	1.2	0.7	0.9	4.0	3.8	4.4	4.6	4.4	3.9	4.8
Petrochemical Feed	12.6	12.6	13.4	13.6	14.1	13.6	13.8	15.9	16.1	14.9
Petroleum Coke	2.6	2.2	3.4	2.3	2.5	2.7	2.9	2.5	4.3	5.2
Waxes and Miscellaneous	3.4	3.7	2.7	2.7	2.9	2.7	2.7	2.8	3.2	3.0
Coal	0.4	0.4	0.8	0.6	0.5	0.6	0.6	0.5	0.5	0.5
Natural Gas	4.1	3.9	3.5	3.9	5.0	4.9	4.9	5.1	5.0	5.3
Transportation										
Lubricants	1.8	1.6	1.6	1.7	1.7	1.7	1.6	1.7	1.8	1.8
Total	68.7	68.3	70.2	73.0	78.1	78.7	80.0	83.2	85.0	89.8

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Table 12. U.S. Carbon Dioxide Emissions from Industrial Processes, 1990-1999
(Million Metric Tons Carbon Equivalent)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Cement Manufacture										
Clinker Production	8.90	8.66	8.75	9.25	9.82	9.85	9.91	10.24	10.48	10.71
Masonry Cement	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03
Cement Kiln Dust	0.18	0.17	0.18	0.19	0.20	0.20	0.20	0.20	0.21	0.21
Cement Subtotal	9.09	8.85	8.94	9.46	10.04	10.07	10.13	10.47	10.72	10.95
Other Industrial										
<i>Limestone Consumption</i>										
Lime Manufacture	3.39	3.36	3.47	3.58	3.73	3.96	4.11	4.22	4.30	4.39
Iron Smelting	0.47	0.44	0.37	0.31	0.30	0.31	0.30	0.31	0.30	0.28
Steelmaking	0.08	0.09	0.07	0.13	0.15	0.14	0.11	0.09	0.10	0.07
Copper Refining	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.04
Glass Manufacture	0.03	0.03	0.04	0.05	0.08	0.09	0.05	0.02	0.05	0.05
Flue Gas Desulfurization	0.18	0.19	0.19	0.18	0.19	0.24	0.26	0.28	0.27	0.27
Dolomite Manufacture	0.13	0.10	0.08	0.07	0.07	0.06	0.09	0.09	0.09	0.09
<i>Limestone Subtotal</i>	<i>4.33</i>	<i>4.24</i>	<i>4.27</i>	<i>4.36</i>	<i>4.57</i>	<i>4.85</i>	<i>4.98</i>	<i>5.05</i>	<i>5.15</i>	<i>5.19</i>
Soda Ash Manufacture	0.92	0.92	0.94	0.91	0.92	1.04	1.03	1.08	1.04	1.06
<i>Soda Ash Consumption</i>										
Glass Manufacture	*	*	*	*	*	*	*	*	*	*
Flue Gas Desulfurization	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
Sodium Silicate	0.05	0.05	0.05	0.06	0.06	0.07	0.06	0.07	0.07	0.06
Sodium Tripolyphosphate	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.01
<i>Soda Ash Subtotal</i>	<i>0.10</i>	<i>0.10</i>	<i>0.10</i>	<i>0.11</i>	<i>0.11</i>	<i>0.13</i>	<i>0.12</i>	<i>0.14</i>	<i>0.11</i>	<i>0.10</i>
Carbon Dioxide Manufacture . . .	0.24	0.25	0.26	0.26	0.27	0.29	0.30	0.31	0.32	0.34
Aluminum Manufacture	1.62	1.65	1.62	1.48	1.32	1.35	1.43	1.44	1.48	1.52
Shale Oil Production	0.05	*	*	*	*	*	*	*	*	*
Other Industrial Subtotal . . .	7.27	7.16	7.19	7.12	7.19	7.65	7.86	8.02	8.11	8.21
Total	16.36	16.02	16.14	16.58	17.23	17.72	17.99	18.49	18.83	19.15

*Less than 50,000 metric tons carbon equivalent.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter.

Carbon Dioxide Emissions

Table 13. Carbon Emissions Coefficients at Full Combustion, 1990-1999
(Million Metric Tons Carbon per Quadrillion Btu)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Petroleum										
Motor Gasoline	19.41	19.41	19.42	19.43	19.45	19.38	19.36	19.35	19.36	19.36
Liquefied Petroleum Gases . . .	16.99	16.98	16.99	16.97	17.01	17.00	16.99	16.99	16.99	16.99
Jet Fuel	19.40	19.40	19.39	19.37	19.35	19.34	19.33	19.33	19.33	19.33
Distillate Fuel	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Residual Fuel (Electric Utility) . .	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29
Residual Fuel (All Other)	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49
Asphalt and Road Oil	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62
Lubricants	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24
Petrochemical Feed	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37
Aviation Gasoline	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Kerosene	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Special Naphtha	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86
Waxes and Miscellaneous	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81
Other Petroleum	17.46	17.83	17.39	16.12	16.36	15.69	16.27	16.57	15.59	14.84
Coal: Residential/Commercial . .	25.92	26.00	26.13	25.97	25.95	26.00	25.92	26.00	26.00	26.00
Coal: Industrial Coking	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.56	25.56	25.56
Coal: Other Industrial	25.58	25.60	25.62	25.61	25.63	25.63	25.61	25.63	25.63	25.63
Coal: Electric Utility	25.68	25.69	25.69	25.71	25.72	25.74	25.74	25.76	25.76	25.76
Flared Gas	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92
Natural Gas	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47
Crude Oil	20.16	20.18	20.22	20.22	20.21	20.23	20.25	20.24	20.24	20.19

P = preliminary data.

Sources: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999), Appendix B, pp. 103-108, and estimates presented in this report.

3. Methane Emissions

Overview

U.S. Anthropogenic Methane Emissions, 1990-1999

	Methane	Carbon Equivalent
Estimated 1999 Emissions (Million Metric Tons)	28.8	164.7
Change Compared to 1998 (Million Metric Tons)	-0.5	-3.0
Change from 1998 (Percent)	-1.8%	-1.8%
Change Compared to 1990 (Million Metric Tons)	-3.0	-17.1
Change from 1990 (Percent)	-9.4%	-9.4%

U.S. anthropogenic methane emissions totaled 28.8 million metric tons in 1999, a decline of about 0.5 million metric tons from 1998 levels (Table 14). The decline is primarily the result of increased methane recovery for energy use at U.S. landfills, and to a lesser extent reductions in emissions from animal waste, coal mining, and petroleum systems. To be eligible for the tax credit included in Section 29 of the Windfall Profits Tax Act of 1980, methane recovery systems at landfills must have been operational by June 30, 1998. As the last recovery projects installed by the tax credit deadline came on line full-time, methane recovery for energy at U.S. landfills rose from 1.7 million metric tons to 2.1 million metric tons. Meanwhile, total U.S. coal production in 1999 fell for the first time in 5 years due to a drop in coal exports and nearly flat demand from electric utilities, lowering methane emissions by about 0.1 million metric tons.³⁰ At the same time, domestic oil production fell, decreasing methane emissions from petroleum systems, and swine

populations declined, lowering emissions from the solid waste of animals.

Total 1999 methane emissions were 3.0 million metric tons below the 1990 level, a decrease equivalent to 17.1 million metric tons of carbon, or roughly 0.9 percent of total U.S. anthropogenic greenhouse gas emissions. In addition to a 2.3 million metric ton decrease in methane emissions from landfills since 1990, there has also been a 1.4 million metric ton decrease in methane emissions from coal mines since 1990 (Table 14). The 32-percent decline in emissions from coal mining is the result of a fourfold increase in methane recovery from coal mines and a shift in production away from some of the gassiest mines in Appalachia. Overall, methane emissions account for about 9 percent of total U.S. greenhouse gas emissions weighted by global warming potential.³¹

Methane emissions estimates are much more uncertain than carbon dioxide emissions estimates. Methane emissions usually are accidental or incidental to biological processes and may not be metered in any systematic way.³² Thus, methane emission estimates must often

Principal Sources of U.S. Anthropogenic Methane Emissions, 1990-1999

Source	Million Metric Tons Methane		Percent Change	
	1990	1999	1990-1999	1998-1999
Energy	11.9	10.6	-11.5%	-1.2%
Waste Management	11.4	9.1	-20.1%	-3.7%
Agriculture	8.3	9.0	8.1%	-0.4%
Industrial Processes	0.1	0.1	11.2%	-2.0%

³⁰Energy Information Administration, *U.S. Coal Supply and Demand: 1999 Review*, web site www.eia.doe.gov/fuelcoal.html.

³¹For a definition of global warming potential, see Chapter 1.

³²Wherever possible, estimates of methane emissions are based on measured data. In some cases, however, measured data are incomplete or unavailable. In the absence of measured data, emissions are calculated by multiplying some known activity data, such as coal production or natural gas throughput, by an emissions factor derived from a small sample of the relevant emissions source or through laboratory experiments. For a more detailed discussion of where measured data were used and how emissions factors were developed, see Appendix A, "Estimation Methods." The absence of measured emissions data for most sources of methane emissions and the reliance on emissions factors represent a source of uncertainty (see Appendix C, "Uncertainty in Emissions Estimates"). Appendixes for this report are available on web site www.eia.doe.gov/oiaf/1605/ggrpt/index.html.

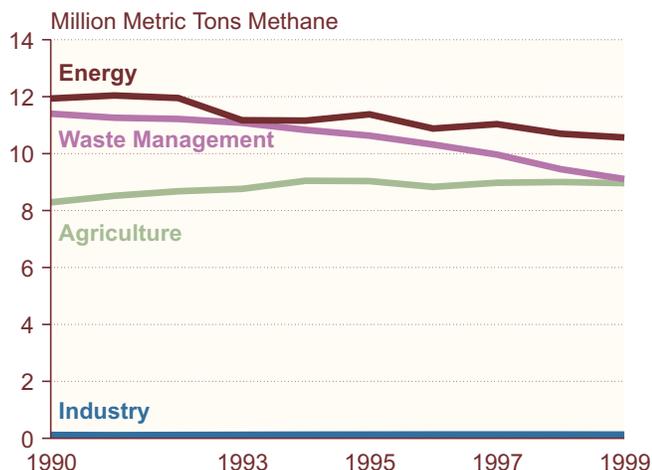
rely on proxy measurements. Considerable effort has been devoted to improving estimation methods. For example, the IPCC has convened expert workshops on best practices for emissions estimation. However, with very little additional sample or activity data being gathered, the marginal improvements associated with revised methods are limited. U.S. anthropogenic methane emissions for 1999 also include preliminary data for several key sources; thus, the overall estimate is preliminary.

Methane emissions from two key sources—coal mining and natural gas systems—are preliminary. These sources represent almost one-third of all U.S. methane emissions. Coal production data on a mine-by-mine basis are collected on Form EIA-7A and typically are not finalized until December following the data year. Estimates of methane emissions from ventilation and degasification systems in coal mines in 1999 have been scaled to reflect a decrease in national production centered in Appalachia and the Illinois basins— areas with predominantly underground operations and the preponderance of ventilation and degasification emissions. Estimated emissions from natural gas systems are preliminary because 1999 data for transmission and distribution pipelines are not yet available.

Energy Sources

U.S. methane emissions from energy sources were estimated at 10.6 million metric tons in 1999, down by 0.13 million metric tons from 1998 and by 1.4 million metric tons from 1990 (Figure 4). Both the decline in 1999 and the drop since 1990 can be traced primarily to decreased

Figure 4. U.S. Emissions of Methane by Source, 1990-1999



Source: Estimates presented in this chapter.

emissions from coal mines and, to a lesser extent, to lower emissions from petroleum systems and stationary combustion. Emissions from coal mines dropped by 32 percent (1.4 million metric tons) between 1990 and 1999. The decline resulted from increased capture and use of methane from coal mine degasification systems and a shift in production away from some of the Nation's gassiest underground mines, in Appalachia. Between 1990 and 1999, the share of coal production represented by underground mines declined from 41 percent to 36 percent. Methane emissions from petroleum systems dropped from 1.29 million metric tons in 1990 to 1.04 million metric tons in 1999. A decrease of 0.15 million metric tons in estimated emissions from stationary combustion made a smaller contribution to the overall drop in emissions from energy sources between 1990 and 1999.

Together, the declines in emissions from coal mining, petroleum systems, and stationary combustion more than compensated for an increase of 0.41 million metric tons in emissions from the natural gas system, attributed to increasing U.S. consumption of natural gas between 1990 and 1999. Overall, annual estimates of methane emissions from energy sources in this report are about 1 million metric tons higher than those that appeared in previous editions of *Emissions of Greenhouse Gases in the United States* due to the first-time addition of much more comprehensive estimates of emissions from petroleum systems (see box on page 34).

Coal Mining

The preliminary estimate of methane emissions from coal mines for 1999 is 2.88 million metric tons (Table 15), a decrease of 4.6 percent from the 1998 level.³³ The decrease can be traced to coal production levels, which fell for the first time in 5 years. U.S. coal production dropped from 1.12 billion short tons in 1998 to 1.09

U.S. Methane Emissions from Coal Mining, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Methane)	2.9
Change Compared to 1998 (Million Metric Tons Methane)	-0.1
Change from 1998 (Percent)	-4.6%
Change Compared to 1990 (Million Metric Tons Methane)	-1.4
Change from 1990 (Percent)	-32.5%

³³Further details on emissions from abandoned coal mines are available in Appendix D, "Emissions Sources Excluded," web site www.eia.doe.gov/oiaf/1605/ggrpt/index.html.

billion short tons in 1999. The decline was primarily attributable to a 37 million short ton decrease in production in Appalachia, a region dominated by underground mining. In contrast, production in Wyoming, nearly all from surface mines, grew from 314 million short tons to 335 million short tons. Metallurgical coal exports to Europe—a key market for eastern U.S. coal—dropped by 30 percent, and increased nuclear generation east of the Mississippi River dampened growth in the electric utility market.³⁴

Between 1990 and 1999, methane emissions from coal mines dropped by 32 percent from the 1990 level of 4.26 million metric tons. The decline is attributed to three important trends: (1) methane recovery from active coal mines for use as an energy resource increased from 0.25 million metric tons in 1990 to about 1 million metric tons in 1999; (2) methane drainage from degasification in active mines decreased by 0.3 million metric tons between 1990 and 1999; and (3) methane emissions from ventilation systems at gassy mines dropped by about 0.4 million metric tons between 1990 and 1999 (Table 15).³⁵

Natural Gas Production, Processing, and Distribution

U.S. Methane Emissions from Natural Gas Systems, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Methane)	6.0
Change Compared to 1998 (Million Metric Tons Methane)	0.0
Change from 1998 (Percent)	-0.3%
Change Compared to 1990 (Million Metric Tons Methane)	0.4
Change from 1990 (Percent)	7.9%

At 5.99 million metric tons, 1999 estimated methane emissions from oil and gas production, processing, and distribution rose slightly from the revised estimate of 5.95 million metric tons for 1998 (Table 16). The 0.7-percent increase can be traced in part to a 17-percent increase in gas withdrawals from storage that offset a

1.4-percent reduction in gross gas withdrawals. The 1999 estimate is preliminary, however, because pipeline data for 1999 have not been finalized. The estimated 1999 emissions level is 7.4 percent above 1990 levels, with about 40 percent of the increase attributable to a 10.4-percent increase in gross gas withdrawals and 55 percent due to a 17-percent increase in distribution main pipeline.³⁶ The estimates of methane emissions from natural gas production, processing, and distribution presented here are about 0.1 million metric tons lower than those that appeared in previous editions of *Emissions of Greenhouse Gases in the United States* because methane emissions from oil wells and oil refining and transport are now included in estimates of methane emissions from petroleum systems (see box on page 34).

Petroleum Systems

U.S. Methane Emissions from Petroleum Systems, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Methane)	1.0
Change Compared to 1998 (Million Metric Tons Methane)	-0.1
Change from 1998 (Percent)	-5.8%
Change Compared to 1990 (Million Metric Tons Methane)	-0.2
Change from 1990 (Percent)	-19.3%

Approximately 97 percent of all emissions from petroleum systems occur during exploration and production. Of the approximately 1 million metric tons of emissions annually from this source, 90 percent can be traced to venting, of which nearly half is attributable to venting from oil tanks (Table 17). A much smaller portion of methane emissions from petroleum systems can be traced to refineries and transportation of crude oil. Overall, methane emissions from petroleum systems are estimated at 1.04 million metric tons in 1999, down from 1.11 million metric tons in 1998 and 1.29 million metric tons in 1990. Domestic oil production in 1999 was approximately 81 percent of the 1990 level, accounting for the decline in methane emissions from this source.

³⁴Energy Information Administration, *U.S. Coal Supply and Demand: 1999 Review*, web site www.eia.doe.gov/fuelcoal.html.

³⁵The EPA believes that a significant portion of methane recovery from coal mines should not be deducted from current-year emissions, because the gas is being drained from coal seams that will be mined only in future years, if at all. The relationship between estimates of emissions from degasification and estimates of gas recovery is under review and may be revised in the future.

³⁶The EPA estimates that the companies participating in the Natural Gas STAR program together avoided more than 468,000 metric tons of methane emissions in 1998 and 537,000 metric tons in 1999. Program participants report annually on emissions reductions achieved through such activities as equipment replacement, enhanced inspection and maintenance, and improved operations management. Participating companies may either use their own techniques to estimate reductions achieved or employ default values developed by the EPA and the Gas Research Institute.

Comprehensive Estimates of Methane Emissions from Petroleum Systems Added This Year

This year marks the first time that comprehensive estimates of methane emissions from petroleum systems appear in *Emissions of Greenhouse Gases in the United States*. Previously, the only estimates for emissions from the petroleum industry included in this report were for emissions from oil wells and from oil refining and transportation. Because those two sources together accounted for only a little more than 0.1 million metric tons of methane emissions annually, the estimates were presented jointly with estimates of emissions from natural gas systems, under the heading "Oil and Gas Production, Processing, and Distribution." This year's report adds estimates of methane emissions from oil exploration and production, which exceeded 1 million metric tons annually between 1990 and 1999.

Estimates of methane emissions from oil exploration and production, included in this report under the heading "Petroleum Systems," are derived from a study completed by the U.S. Environmental Protection

Agency's Office of Air and Radiation, *Draft Estimates of Methane Emissions from the U.S. Oil Industry*. Although not in final form, the report is cited in EPA's most recent national inventory of U.S. greenhouse gas emissions.^a The draft report concludes that there are significant methane emissions from oil production activities, attributable to a small number of system components. Most notably, venting from crude oil storage tanks accounts for nearly 0.4 million metric tons of methane emissions.

The estimates in the EPA draft report were derived by developing activity and emissions factors for 70 petroleum system components. Activity and emissions factors were developed from literature surveys and input from oil industry experts. Activity data were developed for 1995 and then scaled to commonly available metrics, such as number of oil wells and gross production, for all other years. The emissions factors were assumed to remain constant over time.

^aU.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), p. 2-3, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

Stationary Combustion

U.S. Methane Emissions from Stationary Combustion, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Methane)	0.41
Change Compared to 1998 (Million Metric Tons Methane)	0.03
Change from 1998 (Percent)	6.6%
Change Compared to 1990 (Million Metric Tons Methane)	-0.15
Change from 1990 (Percent)	-26.7%

U.S. methane emissions from stationary combustion in 1999 were 412 thousand metric tons, up by 6.6 percent from 1998 levels but 27 percent below 1990 levels (Table 18). Residential consumption of firewood typically accounts for about 85 percent of methane emissions from stationary combustion. Methane emissions are the result of incomplete combustion, and residential woodstoves and fireplaces provide much less efficient combustion than industrial or utility boilers. Estimates of residential wood combustion are, however, very

uncertain.³⁷ The universe of wood consumers is large and heterogeneous, and wood for residential consumption is typically obtained from sources outside the documented economy. EIA relies on its Residential Energy Consumption Survey (RECS), which is fielded every 3 to 4 years, to estimate residential wood consumption. Residential wood consumption data are derived from the 1990, 1994 and 1997 RECS. Intervening and subsequent years are scaled to heating degree-days. For the third consecutive year, the U.S. experienced warmer than average winter temperatures, driving down estimates of wood consumption from more typical levels seen between 1990 and 1996.

Mobile Combustion

Estimated U.S. methane emissions from mobile combustion in 1999 were 244 thousand metric tons, up by 1.5 percent from 1998 levels but 0.6 percent below 1990 levels (Table 19). Emissions from passenger cars have declined since 1990 as older cars with catalytic converters that are less efficient at destroying methane have been taken off the road. From 1993 to 1996, however, rapid growth in the fleet of light-duty trucks and the related increase in methane emissions offset the declines from passenger cars. Since 1997, emissions from passenger cars and light-duty trucks have been flat, and the

³⁷For a discussion of uncertainty in the estimates of greenhouse gas emissions, see Appendix C, "Uncertainty in Emissions Estimates," web site www.eia.doe.gov/oiaf/1605/ggrpt/index.html.

U.S. Methane Emissions from Mobile Combustion, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Methane)	0.24
Change Compared to 1998 (Million Metric Tons Methane)	*
Change from 1998 (Percent)	1.5%
Change Compared to 1990 (Million Metric Tons Methane)	*
Change from 1990 (Percent)	-0.6%

*Less than 0.05 million metric tons.

small growth in emissions over that time is attributable to increased fuel consumption by heavy trucks and other forms of transport such as ships, construction equipment, and small commercial aircraft.

Waste Management

Methane emissions from waste management account for 32 percent of U.S. anthropogenic methane emissions (Figure 4). This portion has been declining from its 1990 level of 36 percent due to a 2.3 million metric ton drop in emissions from landfills. Landfills represent 98 percent of the 9.1 million metric tons of methane emissions from waste management and remain the single largest source of U.S. anthropogenic methane emissions (Table 14). The remainder of emissions from waste management are associated with domestic wastewater treatment. Estimated emissions from waste management would increase if sufficient information were available to estimate emissions from industrial wastewater treatment.³⁸

Landfills

U.S. Methane Emissions from Landfills, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Methane)	8.9
Change Compared to 1998 (Million Metric Tons Methane)	-0.3
Change from 1998 (Percent)	-3.7%
Change Compared to 1990 (Million Metric Tons Methane)	-2.3
Change from 1990 (Percent)	-20.5%

Despite a record level of municipal solid waste reaching U.S. landfills in 1999 (Figure 5),³⁹ estimated methane emissions from landfills dropped to 8.94 million metric tons, 3.7 percent below the 1998 level of 9.29 million metric tons and 2.3 million metric tons or 21 percent below 1990 levels (Table 20). This dramatic decrease is directly attributable to a 2.7 million metric ton increase in methane captured that otherwise would have been emitted to the atmosphere. Of the 3.6 million metric tons of methane believed to be captured from this source, 2.07 million metric tons were recovered for energy use. The remainder was recovered and flared. While estimates of methane recovered and disposed of in both manners are drawn from data collected by EPA's Landfill Methane Outreach Program,⁴⁰ there is less uncertainty in the estimate of methane recovered and used for energy because these projects are reported directly by their principals. In contrast, estimates of methane recovered and flared are derived from sales data reported to EPA by flare manufacturers.

The rapid growth in methane recovery has resulted from a combination of regulatory and tax policy. The Federal Section 29 (of the Internal Revenue Code) tax credit for alternative energy sources, including landfill gas, added to the tax code as part of the Crude Oil Windfall Profits Act of 1980, provides an inflation-adjusted credit that currently is equivalent to \$6.00 per barrel of oil equivalent of qualified fuels. However, the tax credit for new facilities expired on June 30, 1998, and, absent a similar subsidy, the number of additional landfill gas-to-energy projects that are commercially viable is limited. More recently, increases in methane recovery have resulted from the implementation of EPA's New Source

Figure 5. U.S. Solid Waste Generated and Landfilled, 1990-1999



Source: "Nationwide Survey: The State of Garbage in America, 1999," *Biocycle* (various years).

³⁸For further details see Appendix D, "Emissions Sources Excluded," web site www.eia.doe.gov/oiaf/1605/ggrpt/index.html.

³⁹"Nationwide Survey: The State of Garbage in America, 1999," *Biocycle* (April 2000).

⁴⁰See web site www.epa.gov/lmop.

Methane Emissions

Performance Standards and Emission Guidelines, which require all landfills with more than 2.5 million metric tons of waste in place and annual emissions of nonmethane volatile organic compounds (NMVOCs) exceeding 50 metric tons to collect and burn their landfill gas, either by flaring or as an energy resource.⁴¹

Currently, Section 45 of the Internal Revenue Code contains a provision that grants a tax credit—valued at approximately 1.7 cents per kilowatt-hour—for electricity generated from wind, closed-loop biomass, or poultry waste.⁴² Representative Camp has introduced a bill, H.R. 3466, to the House Committee on Ways and Means that would qualify landfill gas as an alternative energy source under Section 45. The bill would also provide an equivalent subsidy to other energy uses of landfill gas. Passage of this bill during the current session of Congress is uncertain. Absent this or an alternative source of subsidy, it is likely that the preponderance of future methane recovery at landfills may result in flaring.

Domestic and Commercial Wastewater Treatment

U.S. Methane Emissions from Domestic and Commercial Wastewater Treatment, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Methane)	0.16
Change Compared to 1998 (Million Metric Tons Methane)	*
Change from 1998 (Percent)	0.9%
Change Compared to 1990 (Million Metric Tons Methane)	0.01
Change from 1990 (Percent)	9.3%

*Less than 0.05 million metric tons.

Methane emissions from domestic and commercial wastewater treatment are a function of the share of organic matter in the wastewater stream and the conditions under which it decomposes. Wastewater may be treated aerobically or anaerobically. If it is treated aerobically, methane emissions will be low. Under anaerobic conditions, methane emissions will be high. There is little data available on wastewater treatment methods. Data on flaring or energy recovery from methane generated by wastewater is also sparse. EIA believes that emissions from this source are relatively small, representing on the order of 0.6 percent of all U.S. methane emissions. Thus, emissions are estimated using a default per-capita emissions factor and U.S. population data.

⁴¹EPA's voluntary Landfill Methane Outreach Program has also contributed to the increase in methane recovery from U.S. landfills.

⁴²Solid Waste Association of North America, web site [www.swana.com/Whypolicy\(3\).htm](http://www.swana.com/Whypolicy(3).htm).

With the U.S. population growing slowly, methane emissions from domestic and commercial wastewater treatment are estimated to have grown by 0.9 percent between 1998 and 1999 to 0.16 million metric tons. This is about 9.3 percent above the 1990 level of 0.15 million metric tons (Table 14). The EPA is conducting research in this area. If additional information becomes available, EIA will review it and revise the estimation method accordingly.

Agricultural Sources

At an estimated 9.0 million metric tons, methane emissions from agricultural activities represent 31 percent of total U.S. anthropogenic methane emissions. (Table 14). Ninety-four percent of methane emissions from agricultural activities result from livestock management. About 64 percent of these emissions can be traced to enteric fermentation in ruminant animals and the remainder to anaerobic decomposition of livestock wastes. A small portion of U.S. methane emissions result from crop residue burning and wetland rice cultivation. Estimated agricultural methane emissions dropped slightly between 1998 and 1999 due mainly to a decrease in swine populations that lowered emissions from the solid waste of domesticated livestock.

Enteric Fermentation in Domesticated Animals

U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Methane)	5.4
Change Compared to 1998 (Million Metric Tons Methane)	*
Change from 1998 (Percent)	-0.2%
Change Compared to 1990 (Million Metric Tons Methane)	0.2
Change from 1990 (Percent)	4.6%

*Less than 0.05 million metric tons.

In 1999, estimated methane emissions from enteric fermentation in domesticated animals remained essentially unchanged at 5.4 million metric tons (Table 21). Because cattle account for about 95 percent of all emissions from enteric fermentation, trends in emissions correlate with trends in cattle populations. The flat trend results from a

slowly decreasing cattle population, offset by a slowly increasing average size for cattle. Average cattle size (excluding calves) reached a 20-year high in 1999. Animal size is a principal determinant of energy intake requirements, which relate directly to methane emissions. Emissions remain 4.6 percent above 1990 levels, primarily due to an average 6.4-percent growth in average cattle size between 1990 and 1999.⁴³ Meanwhile, cattle populations have fluctuated in a cyclical pattern, settling in 1999 at levels very similar to those seen in 1990.

Solid Waste of Domesticated Animals

U.S. Methane Emissions from Solid Waste of Domesticated Animals, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Methane)	3.0
Change Compared to 1998 (Million Metric Tons Methane)	-0.1
Change from 1998 (Percent)	-2.0%
Change Compared to 1990 (Million Metric Tons Methane)	0.3
Change from 1990 (Percent)	12.5%

Estimated methane emissions from the solid waste of domesticated animals declined from 3,086 thousand metric tons in 1998 to 3,026 thousand metric tons in 1999 (Table 22). The decrease was the result of a 4-percent drop in populations of market swine and a 7-percent decline in populations of breeding swine, which decreased methane emissions by 75 thousand metric tons. In the absence of the population declines, overall methane emissions from the waste of domesticated animals would have increased slightly. There has also been a shift of swine populations to larger livestock operations, which are believed to be more likely to manage waste using liquid systems that tend to promote methane generation.⁴⁴ EIA does not have sufficient data to substantiate that belief at this time. If true, however, it would likely change the trend in emissions from this source from slightly negative to slightly positive. Despite the apparent declines, estimated 1999 emission levels were still approximately 337 thousand metric tons above 1990 levels due to a general increase in the size of cattle over the last decade and a 12-percent increase in the population of market swine.

Rice Cultivation

Estimated methane emissions from U.S. rice cultivation continued to grow in 1999, due to an increase in the acreage harvested. In 1999, estimated emissions reached 0.50 million metric tons, the highest level since the early 1980s and 23 percent above 1990 levels (Table 14). Because data for rice harvested in Florida were unavailable for 1999, EIA assumed that the level of cultivation for Florida remained stable from 1998. This is likely to have a very limited effect on overall emission estimates, because Florida accounts for less than 1 percent of all rice harvested in the United States.

Burning of Crop Residues

Crop residue burning, being the smallest contributor to agricultural greenhouse gas emissions, represents on the order of 0.1 percent of total U.S. methane emissions. Estimated 1999 methane emissions from the burning of crop residues were 0.04 million metric tons, down by 2.8 percent from 1998 levels (Table 14). The small decrease is attributable mainly to reduced corn, soybean, and wheat production. Emissions remain 10 percent (3,000 metric tons) above 1990 levels.

The 1999 estimate of methane emissions from crop residue burning reflects a small modification to the estimation method. In last year's report, the portion of California rice crop residues assumed to be burned was raised from 3 percent used for all other crops to a range that declined from a high of 99 percent in 1990 to 50 percent in 1996 and beyond. The assumption has been revised again to reflect improved data collected by the EPA.⁴⁵ The most recent EPA estimate of the portion of rice crop residues in California that is burned ranges from 43 percent in 1990 down to 16 percent in 1997 and up to 19 percent in 1998 and 1999. The effect of this change on the overall estimate of methane emissions from crop residue burning is limited, however, because less than 2 percent of emissions from this source are attributable to California rice crop residues.

Industrial Sources

Chemical Production

The preliminary estimate of methane emissions from U.S. chemical production in 1999 is 77 thousand metric tons, 21 thousand metric tons higher than in 1990 (Table 23). The 1999 number remains preliminary pending

⁴³U.S. Department of Agriculture, National Agricultural and Statistics Service, Livestock, web site www.nass.usda.gov:81/ipedb.

⁴⁴U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000) p. 5-5, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

⁴⁵U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), p. 5-23, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

Methane Emissions

updated production data for five chemicals: methanol, carbon black, ethylene, ethylene dichloride, and styrene. Methane emissions from chemical production were essentially flat in 1997 and 1998.

Iron and Steel Production

With production of pig iron declining by 4 percent, production of sinter dropping by 6 percent, and production of coke falling by 9 percent, estimated methane emissions from iron and steel production were 54 thousand metric tons in 1999, down by 3 thousand metric tons from 1998 levels and 13 percent below the 1990 level of 62 thousand metric tons (Table 23). A general pattern of reduced iron and steel production has resulted in flat or declining methane emissions from this source over the past decade.

U.S. Methane Emissions from Industrial Sources, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Methane)	0.13
Change Compared to 1998 (Million Metric Tons Methane)	*
Change from 1998 (<i>Percent</i>)	-2.0%
Change Compared to 1990 (Million Metric Tons Methane)	0.01
Change from 1990 (<i>Percent</i>)	11.2%

*Less than 0.05 million metric tons.

Table 14. U.S. Methane Emissions from Anthropogenic Sources, 1990-1999
(Million Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Energy Sources										
Coal Mining	4.26	4.12	3.97	3.34	3.36	3.43	2.95	3.10	3.02	2.88
Natural Gas Systems	5.58	5.80	5.86	5.85	5.86	5.95	5.97	6.12	5.95	5.99
Petroleum Systems	1.29	1.30	1.26	1.20	1.17	1.16	1.14	1.14	1.11	1.04
Stationary Combustion	0.56	0.59	0.62	0.54	0.53	0.58	0.58	0.44	0.39	0.41
Mobile Sources	0.25	0.23	0.24	0.24	0.24	0.25	0.24	0.24	0.24	0.24
Total Energy Sources	11.94	12.04	11.95	11.17	11.16	11.38	10.88	11.03	10.70	10.56
Waste Management										
Landfills	11.25	11.11	11.06	10.92	10.68	10.47	10.16	9.80	9.29	8.94
Wastewater Treatment	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Total Waste Management	11.40	11.26	11.22	11.08	10.83	10.63	10.32	9.97	9.45	9.11
Agricultural Sources										
Enteric Fermentation	5.16	5.30	5.39	5.46	5.59	5.61	5.46	5.42	5.41	5.40
Animal Waste	2.69	2.79	2.81	2.87	2.95	2.95	2.93	3.08	3.09	3.03
Rice Paddies	0.40	0.39	0.44	0.40	0.47	0.44	0.40	0.44	0.47	0.50
Crop Residue Burning	0.04	0.03	0.04	0.03	0.04	0.03	0.04	0.04	0.04	0.04
Total Agricultural Sources	8.29	8.52	8.68	8.76	9.05	9.03	8.83	8.98	9.00	8.96
Industrial Processes	0.12	0.11	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.13
Total	31.74	31.93	31.96	31.14	31.17	31.18	30.16	30.11	29.29	28.77

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: EIA estimates presented in this chapter. Emissions calculations based on Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.83-4.84, web site www.ipcc.ch/pub/guide.htm; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

Methane Emissions

Table 15. U.S. Methane Emissions from Coal Mining and Post-Mining Activities, 1990-1999
(Million Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Surface Mining										
Mining.	0.43	0.42	0.42	0.42	0.45	0.45	0.46	0.47	0.49	0.49
Post-Mining.	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Underground Mining										
Ventilation (Gassy Mines)	2.13	2.04	2.10	1.82	1.85	1.91	1.71	1.79	1.80	1.70
Ventilation (Nongassy Mines)	0.03	0.03	0.02	0.02	0.03	0.03	0.04	0.04	0.03	0.03
Degasification.	1.26	1.23	1.17	1.05	1.06	1.21	1.02	1.06	1.04	0.98
Post-Mining.	0.64	0.61	0.61	0.53	0.60	0.60	0.62	0.63	0.63	0.59
Methane Recovery for Energy (-).	0.25	0.25	0.39	0.53	0.67	0.80	0.94	0.94	1.02	0.96
Net Emissions	4.26	4.12	3.97	3.34	3.36	3.43	2.95	3.10	3.02	2.88

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: Coal production numbers from Energy Information Administration, *Coal Production*, DOE/EIA-0118 (Washington, DC, various years), and *Coal Industry Annual*, DOE/EIA-0584 (Washington, DC, 1995-1998). Methane recovery rates from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress* (Washington, DC, April 1993), pp. 3-19-3-24; and U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines*, EPA-430-R-97-020 (Washington, DC, September 1997). Ventilation data for 1985, 1988, 1990, and 1993 provided by G. Finfinger, U.S. Department of the Interior, Bureau of Mines, Pittsburgh Research Center. Ventilation data for 1994 and 1996-1998 provided by U.S. Environmental Protection Agency, Climate Protection Division, Coalbed Methane Outreach Program.

Table 16. U.S. Methane Emissions from Natural Gas Systems, 1990-1999
(Million Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Production	1.47	1.49	1.49	1.51	1.55	1.57	1.58	1.65	1.67	1.63
Gas Processing	0.65	0.71	0.70	0.71	0.71	0.72	0.73	0.71	0.70	0.71
Transmission and Storage	2.10	2.21	2.23	2.15	2.11	2.14	2.11	2.20	1.98	2.06
Distribution	1.36	1.39	1.44	1.48	1.49	1.52	1.55	1.55	1.59	1.59
Total	5.58	5.80	5.86	5.85	5.86	5.95	5.97	6.12	5.95	5.99

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: National Risk Management Research Laboratory, *Methane Emissions From the Natural Gas Industry*, Vol. 2, Technical Report, GRI-94/0257.1 and EPA-600-R-96-08 (Research Triangle Park, NC, June 1996), Appendix A; American Gas Association, *Gas Facts* (various years); Energy Information Administration, *Natural Gas Annual*, DOE/EIA-0131 (various years); Energy Information Administration, *Annual Energy Review 1999*, DOE/EIA-0384(99) (Washington, DC, July 2000); Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

Table 17. U.S. Methane Emissions from Petroleum Systems, 1990-1999
(Million Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Refineries	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03
Exploration and Production	1.26	1.27	1.23	1.17	1.14	1.13	1.11	1.11	1.07	1.01
Crude Oil Transportation	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	1.29	1.30	1.26	1.20	1.17	1.16	1.14	1.14	1.11	1.04

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Source: U.S. Environmental Protection Agency, Office of Air and Radiation, *Draft Estimates of Methane Emissions from the U.S. Oil Industry* (Draft Report, Washington, DC).

Methane Emissions

Table 18. U.S. Methane Emissions from Stationary Combustion Sources, 1990-1999
(Thousand Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Residential										
Coal	*	*	*	*	*	*	*	*	*	*
Distillate Fuel	4	4	4	5	4	4	5	5	5	4
Natural Gas	4	4	5	5	5	5	5	5	4	5
LPG	*	*	*	*	*	*	1	1	*	1
Wood	512	541	569	483	474	526	525	382	332	356
Total	521	550	578	493	483	535	535	392	342	365
Commercial										
Coal	1	1	1	1	1	1	1	1	1	1
Distillate Fuel	1	1	1	1	1	1	1	*	*	*
Natural Gas	3	3	3	3	3	4	4	4	4	4
LPG	*	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*	*
Total	5									
Industrial										
Coal	7	6	6	6	6	6	6	6	6	5
Distillate Fuel	1	1	1	1	1	1	1	1	1	1
Natural Gas	11	12	12	13	13	14	14	14	14	14
LPG	2	2	3	2	3	3	3	3	3	3
Wood	4	4	4	4	5	5	5	5	5	6
Total	26	26	26	27	28	28	29	29	28	29
Electric Utility										
Coal	10	10	10	10	10	10	11	11	11	12
Distillate Fuel	1	1	1	1	1	*	*	*	1	1
Natural Gas	*	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*	*
Total	11	11	11	11	11	11	12	12	12	12
Total All Fuels										
Coal	17	17	17	17	17	17	18	18	18	18
Distillate Fuel	7	7	7	7	7	7	7	7	7	6
Natural Gas	19	20	20	21	21	22	23	23	22	22
LPG	3	3	3	3	3	3	4	4	3	4
Wood	517	545	573	488	478	530	530	387	338	363
Total	563	591	620	536	527	580	581	438	387	412

*Less than 500 metric tons of methane.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors*, AP-42, web site www.epa.gov/ttn/chief; Energy Information Administration, *State Energy Data Report 1997*, DOE/EIA-0214(97) (Washington, DC, September 1999); *Monthly Energy Review*, DOE/EIA-0035(00/07) (Washington, DC, July 2000); and *Annual Energy Review 1999*, DOE/EIA-0384(99) (Washington, DC, July 2000).

Table 19. U.S. Methane Emissions from Mobile Sources, 1990-1999
(Thousand Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Motor Vehicles										
Passenger Cars	142	132	131	126	117	109	107	105	105	105
Buses	1	1	1	1	1	1	1	1	1	1
Motorcycles	4	4	4	4	4	4	4	4	4	4
Light-Duty Trucks	63	63	63	75	85	99	92	91	91	91
Other Trucks	12	12	12	13	14	14	15	15	16	16
Total	222	212	212	219	221	228	219	217	217	218
Other Transport	23	23	24	22	22	23	23	21	23	25
Total Transport	245	235	235	241	243	251	242	238	240	244

P = preliminary data.

Sources: Calculations based on vehicle miles traveled from U.S. Department of Transportation, *Federal Highway Statistics*, various years, Table VM-1. Vehicle emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.65-1.75, web site www.ipcc.ch/pub/guide.htm. Distribution of passenger car and light duty truck fleet model years for 1983, 1985, 1988, 1991, and 1994 according to data in the Energy Information Administration's "Residential Transportation Energy Consumption Surveys" for those years. Distribution for passenger cars and light duty trucks in other years computed by interpolation. Distribution of bus and other truck fleet according to model year computed assuming 10-percent attrition per annum of pre-1983 fleet for each year after 1984.

Table 20. U.S. Methane Emissions from Landfills, 1990-1999
(Million Metric Tons Methane)

Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Emissions from Landfills										
With Recovery	10.2	10.3	10.4	10.4	10.5	10.5	10.5	10.5	10.5	10.5
Without Recovery	2.0	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Methane Recovered for Energy (-)	0.7	0.7	0.7	0.8	0.9	1.0	1.1	1.3	1.7	2.1
Methane Assumed Flared (-)	0.3	0.5	0.6	0.8	1.0	1.2	1.4	1.5	1.6	1.6
Net Emissions	11.3	11.1	11.1	10.9	10.7	10.5	10.2	9.8	9.3	8.9

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999).

Sources: Municipal solid waste landfilled from *Biocycle*, "Nationwide Survey: The State of Garbage in America" (1989-1998). Emissions calculations based on S.A. Thorneloe et al., "Estimate of Methane Emissions from U.S. Landfills," Prepared for the U.S. Environmental Protection Agency, Office of Research and Development (April 1994), and D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane," *Global Environmental Change* (December 1992), pp. 311-328. Methane recovered and flared from U.S. Environmental Protection Agency, Office of Air and Radiation, Climate Protection Division, Landfill Methane Outreach Program, web site www.epa.gov/lmop/.

Methane Emissions

Table 21. U.S. Methane Emissions from Enteric Fermentation in Domesticated Animals, 1990-1999
(Million Metric Tons Methane)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Cattle	4.87	5.01	5.10	5.18	5.31	5.35	5.20	5.16	5.15	5.16
Sheep	0.15	0.15	0.14	0.13	0.13	0.12	0.11	0.10	0.10	0.09
Pigs	0.08	0.09	0.09	0.09	0.09	0.09	0.08	0.09	0.09	0.09
Goats.	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01
Horses	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05
Total	5.16	5.30	5.39	5.46	5.59	5.61	5.46	5.42	5.41	5.40

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: Cattle, sheep, and pig population data provided by the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Service. Goat and horse population figures extrapolated from U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture*, 1982, 1987, 1992, and 1997. Emissions calculations based on U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), pp. 159-161, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html; and P.J. Crutzen, I. Aselmann, and W.S. Seiler, "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," *Tellus*, Vol. 38B (1986), pp. 271-284.

Table 22. U.S. Methane Emissions from the Solid Waste of Domesticated Animals, 1990-1999
(Thousand Metric Tons Methane)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Cattle										
Beef Cattle	249	264	271	278	284	286	275	275	273	275
Dairy Cattle	917	923	927	964	1,011	1,045	1,082	1,110	1,112	1,119
Swine										
Market Swine	861	912	924	919	954	931	896	981	1,005	961
Breeding Swine	487	515	506	510	498	482	468	495	476	445
Poultry										
Caged Layers.	83	84	86	88	90	91	92	94	97	100
Broilers	73	77	81	91	95	100	102	105	106	109
Other Animals										
Sheep.	5	5	5	5	4	4	4	4	3	3
Goats	1	1	1	1	1	1	1	1	1	1
Horses	12	11	11	11	12	12	13	13	13	14
Total	2,688	2,792	2,812	2,867	2,949	2,951	2,932	3,076	3,086	3,026

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: Population data for horses and goats extrapolated from U.S. Department of Commerce, Bureau of the Census, *Census of Agriculture*, 1982, 1987, 1992, and 1997. Population data for all other animals from U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch. Typical animal sizes from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress* (Washington, DC, April 1993), p. 6-8. Cattle sizes adjusted by annual slaughter weight from U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Branch. Maximum methane production, and waste management systems used from L.M. Safley, M.E. Casada, et al., *Global Methane Emissions from Livestock and Poultry Manure* (Washington, DC: U.S. Environmental Protection Agency, February 1992), pp. 24-27, and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-230-00-001 (Washington, DC, April 2000). General methane conversion factors from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 4.25, web site www.ipcc.ch/pub/guide.htm. State methane conversion factors for dairy cattle from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

Table 23. U.S. Methane Emissions from Industrial Processes, 1990-1999
(Thousand Metric Tons Methane)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Chemical Production										
Ethylene	17	18	19	19	20	21	22	23	23	23
Ethylene Dichloride	3	2	3	3	3	3	3	4	4	4
Styrene	15	15	16	18	20	21	22	21	21	21
Methanol	8	8	7	10	10	10	11	12	11	11
Carbon Black	14	13	15	16	16	17	17	17	18	18
Total.	56	57	60	66	70	72	75	77	77	77
Iron and Steel Production										
Coke ^a	11	9	9	9	8	9	8	7	7	6
Sinter	6	5	6	6	6	6	6	6	6	5
Pig Iron	45	40	43	43	44	46	44	45	43	42
Total.	62	54	57	58	59	61	59	58	56	54
Total Industrial Processes	117	111	117	124	129	132	134	134	133	130

^aBased on total U.S. production of metallurgical coke, including non-iron and steel uses.

P = preliminary data.

Note: Totals may not equal sum of components due to independent rounding.

Sources: American Iron and Steel Institute, *Annual Statistical Report* (Washington, DC, various years); American Chemical Council, *U.S. Chemical Industry Statistical Handbook* (Washington, DC, various years); and Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.23, web site www.ipcc/pub/guide.htm.

4. Nitrous Oxide Emissions

Overview

U.S. Anthropogenic Nitrous Oxide Emissions, 1990-1999

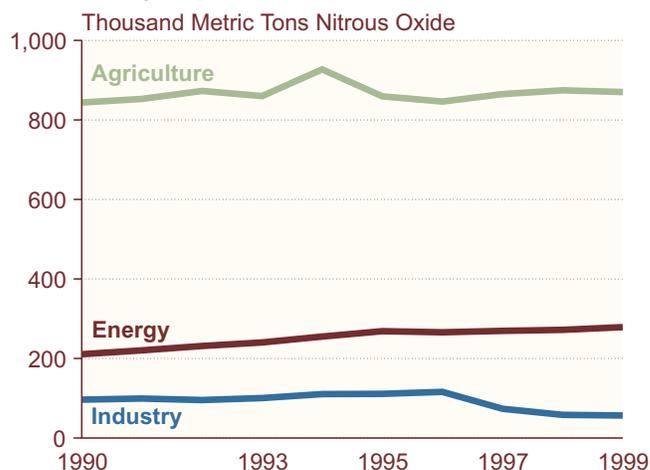
	Nitrous Oxide	Carbon Equivalent
Estimated 1999 Emissions (Thousand Metric Tons)	1,224.2	103,499.2
Change Compared to 1998 (Thousand Metric Tons)	1.3	108.5
Change from 1998 (Percent)	0.1%	0.1%
Change Compared to 1990 (Thousand Metric Tons)	56.6	4,786.6
Change from 1990 (Percent)	4.8%	4.8%

Estimated U.S. anthropogenic nitrous oxide emissions totaled 1,224.2 thousand metric tons in 1999, 0.1 percent more than in 1998 and 5 percent above 1990 levels (Table 24). Nearly all the increase from 1990 levels can be attributed to emissions from the nitrogen fertilization of agricultural soils and emissions from mobile combustion, which grew by 23.3 and 61.5 thousand metric tons, respectively, between 1990 and 1999.

The largest component of U.S. anthropogenic nitrous oxide emissions is emissions from agricultural activities, almost three-quarters of which result from nitrogen fertilization of agricultural soils. Most of the remainder is from the handling of animal waste in managed systems. Small quantities of nitrous oxide are also released from the burning of crop residues. Estimated emissions of nitrous oxide from agricultural sources were 870.1 thousand metric tons in 1999, less than 1 percent below 1998 levels but 3 percent above 1990 levels (Figure 6).

There are large uncertainties connected with the emissions consequences of adding nitrogen to agricultural soils. Models used for estimation are based on limited sources of experimental data.⁴⁶ The uncertainty increases when moving from emissions associated with animal manure to soil mineralization and atmospheric

Figure 6. U.S. Emissions of Nitrous Oxide by Source, 1990-1999



Source: Estimates presented in this chapter.

Principal Sources of U.S. Anthropogenic Nitrous Oxide Emissions, 1990-1999

Source	Thousand Metric Tons Nitrous Oxide		Percent Change	
	1990	1999	1990-1999	1998-1999
Energy Use	210.7	278.9	32.4%	2.5%
Agriculture	843.8	870.1	3.1%	-0.5%
Industrial	96.5	56.6	-41.3%	-2.6%

deposition, where both estimating emissions and partitioning emissions between anthropogenic and biogenic sources become increasingly difficult.

The second-largest source of anthropogenic nitrous oxide emissions is energy consumption, which includes mobile source combustion from passenger cars, buses, motorcycles, and trucks and stationary source combustion from commercial, residential, industrial, and electric utility energy use. Energy use was responsible for the release of 278.9 thousand metric tons of nitrous oxide in 1999, 3 percent higher than in 1998 and 32 percent higher than in 1990.

⁴⁶Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.87-4.100, web site www.ipcc.ch/pub/guide.htm.

Industrial production of adipic acid and nitric acid, which releases nitrous oxide as a byproduct, accounted for emissions of about 56.6 thousand metric tons of nitrous oxide in 1999, a 41-percent decrease from 1990 levels and a 3-percent decline from 1998 levels (Table 24). The large decline in emissions from this source is a result of the implementation of emissions control technology at three of the four adipic acid plants operating in the United States.

Energy Use

U.S. Nitrous Oxide Emissions from Energy Use, 1990-1999

Estimated 1999 Emissions (Thousand Metric Tons Nitrous Oxide)	278.9
Change Compared to 1998 (Thousand Metric Tons Nitrous Oxide)	6.8
Change from 1998 (Percent)	2.5%
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	68.2
Change from 1990 (Percent)	32.4%

Nitrous oxide emissions from both mobile and stationary sources are byproducts of fuel combustion. Estimated 1999 energy-related emissions were 278.9 thousand metric tons, 23 percent of total U.S. anthropogenic nitrous oxide emissions (Table 24). Emissions from energy use are dominated by mobile combustion (82 percent of 1999 totals).

Mobile Combustion

Nitrous oxide emissions from mobile source combustion in 1999 were 227.7 thousand metric tons, 2 percent above 1998 levels (Table 25). In addition to emissions from passenger cars and light-duty trucks, emissions from air, rail, and marine transportation and from farm and construction equipment are also included in the estimates. Ninety-four percent of the emissions can be attributed to motor vehicles (Table 25). Emissions grew rapidly between 1990 and 1995 due to increasing motor vehicle use, the shifting composition of the light-duty vehicle fleet toward light trucks, and the gradual replacement of low emitting pre-1983 vehicles in the fleet with higher emitting post-1983 vehicles. The shift to advanced three-way catalytic converters in 1996 through 1999 model year cars has slowed but not abated emissions growth from this source.

Nitrous oxide emissions from motor vehicles are caused primarily by the conversion of pollutant nitrogen oxides (NO_x) into nitrous oxide (N_2O) by vehicle catalytic converters. The normal operating temperature of catalytic converters is high enough to cause the thermal decomposition of nitrous oxide. Consequently, it is probable that nitrous oxide emissions result primarily from “cold starts” of motor vehicles and from catalytic converters that are defective or operating under abnormal conditions. This implies that the primary determinant of the level of emissions is motor vehicle operating conditions; however, different types of catalytic converters appear to differ systematically in their emissions, and emissions probably vary with engine size. Thus, emissions also depend on the “mix” of vehicle age and type on the road.

Stationary Combustion

During combustion, nitrous oxide is produced as a result of chemical interactions between nitrogen oxides (mostly NO_2) and other combustion products. With most conventional stationary combustion systems, high temperatures destroy almost all nitrous oxide, limiting the quantity that escapes; therefore, emissions from these systems are typically low. In 1999, estimated nitrous oxide emissions from stationary combustion sources were 51.1 thousand metric tons, 4 percent higher than in 1998 and 15 percent higher than in 1990 (Table 26). Nearly two-thirds (63 percent) of the emissions increase from this source between 1990 and 1999 can be attributed to coal-fired electricity generation, which grew in response to the growing demand for electricity and lower costs and improved availability at coal-fired power plants. Coal-fired combustion systems produced 59 percent of the 1999 emissions of nitrous oxide from stationary combustion, and electric utilities accounted for 55 percent of all nitrous oxide emissions from stationary combustion.

Agriculture

On a global scale, agricultural practices contribute approximately 70 percent of anthropogenic nitrous oxide emissions.⁴⁷ Similarly, in the United States, agricultural activities were responsible for 71 percent of 1999 nitrous oxide emissions. Seventy-three percent of agricultural emissions are associated with nitrogen fertilization of agricultural soils (Table 24). Nearly all the remaining agricultural emissions can be traced to the management of the solid waste of domesticated animals. The disposal of crop residues by burning also produces nitrous oxide that is released into the atmosphere; however, the amount is relatively minor, at 1.6 thousand metric tons or 0.2 percent of total U.S. emissions of

⁴⁷A.R. Mosier, “Nitrous Oxide Emissions from Agricultural Soils,” in A.R. van Amstel (ed.), *International IPCC Workshop Proceedings: Methane and Nitrous Oxide, Methods in National Emissions Inventories and Options for Control* (Bilthoven, Netherlands: RIVM, 1993), p. 277.

nitrous oxide from agricultural sources in 1999. Nitrous oxide emissions from agricultural activities grew by 3 percent between 1990 and 1999.

Nitrogen Fertilization of Agricultural Soils

Nitrogen uptake and nitrous oxide emissions occur naturally as a result of nitrification and denitrification processes in soil and crops, generally through bacterial action. When nitrogen compounds are added to the soil, bacterial action is stimulated, and emissions generally increase, unless the application precisely matches plant uptake and soil capture.⁴⁸ Nitrogen may be added to the soil by synthetic or organic fertilizers, nitrogen-fixing crops, and crop residues. Nitrogen-rich soils, called “histosols,” may also stimulate emissions.

Adding excess nitrogen to the soil also enriches ground and surface waters, such as rivers and streams, which generate indirect emissions of nitrous oxide. Additional indirect emissions occur from “atmospheric deposition,” in which soils emit other nitrogen compounds that react to form nitrous oxide in the atmosphere. EIA estimates that a total of 636.8 thousand metric tons of nitrous oxide was released into the atmosphere as a result of direct and indirect emissions associated with fertilization practices in 1999 (Table 27). Estimated emissions increased by 4 percent compared with 1990 and decreased by less than 1 percent compared with 1998. Nitrous oxide emissions from the application of nitrogen-based fertilizers and biological fixation in crops accounted for 61.5 percent of total nitrous oxide emissions from this source during 1999.

Crop Residue Burning

When crop residues are burned, the incomplete combustion of agricultural waste results in the production of nitrous oxide as well as methane (discussed in Chapter

3). In 1999, estimated emissions of nitrous oxide from crop residue burning were 1.6 thousand metric tons, down by 3 percent from 1998 levels (Table 24). The small decrease is mainly attributable to reduced corn, soybean, and wheat production. Emissions from this source remain very small, at 0.1 percent of all U.S. nitrous oxide emissions.

Solid Waste of Domesticated Animals

Estimated 1999 nitrous oxide emissions from animal waste management were about 231.7 thousand metric tons, down by 1 percent from 1998 levels and 1 percent higher than 1990 levels (Table 28), making animal waste the second-largest U.S. agricultural source of nitrous oxide emissions, after nitrogen fertilization of soils. Nitrous oxide emissions from animal waste are dominated by emissions from cattle waste, which account for 94 percent of emissions from the solid waste of domesticated animals. Thus, changes in estimated emissions result primarily from changes in cattle populations. Cattle populations grew during the first half of the decade, leading to higher emissions through 1995, but have since declined slowly, bringing emissions close to 1990 levels.

Nitrous oxide is released as part of the microbial denitrification of animal manure. The total volume of nitrous oxide emissions is a function of animal size and manure production, the amount of nitrogen in the animal waste, and the method of managing the animal waste. Waste managed by a solid storage or pasture range method may emit 20 times the nitrous oxide per unit of nitrogen content than does waste managed in anaerobic lagoon and liquid systems. Generally, solid waste from feedlot beef cattle is managed with the solid storage or pasture range method, accounting for the majority of nitrous oxide emissions. Solid waste from swine is generally managed in anaerobic lagoons and other liquid systems. Anaerobic digestion yields methane emissions but only negligible amounts of nitrous oxide.

Waste Management

Nitrous oxide emissions from waste management are estimated at about 18.5 thousand metric tons for 1999, 2 percent of all U.S. anthropogenic nitrous oxide emissions (Table 24). During 1999, emissions from human sewage in wastewater were responsible for 96 percent of the estimated emissions from this source, and the remainder was associated with waste combustion. Estimated emissions from waste management grew by 12 percent between 1990 and 1999 and by 1 percent between 1998 and 1999. Because of the lack of reliable

U.S. Nitrous Oxide Emissions from Agriculture, 1990-1999

Estimated 1999 Emissions (Thousand Metric Tons Nitrous Oxide)	870.1
Change Compared to 1998 (Thousand Metric Tons Nitrous Oxide)	-4.3
Change from 1998 (Percent)	-0.5%
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	26.3
Change from 1990 (Percent)	3.1%

⁴⁸A.F. Bouwman, “Exchange of Greenhouse Gases Between Terrestrial Ecosystems and the Atmosphere,” in A.F. Bouwman (ed.), *Soils and the Greenhouse Effect* (New York, NY: John Wiley and Sons, 1990).

U.S. Nitrous Oxide Emissions from Waste Management, 1990-1999

Estimated 1999 Emissions (Thousand Metric Tons Nitrous Oxide)	18.5
Change Compared to 1998 (Thousand Metric Tons Nitrous Oxide)	0.2
Change from 1998 (Percent)	1.0%
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	2.0
Change from 1990 (Percent)	11.9%

data and an effective estimation method, no estimate of emissions from industrial wastewater was calculated, leaving estimated emissions from waste management lower than they otherwise would be had a viable estimation method been available.

Waste Combustion

In 1999, estimated nitrous oxide emissions from waste combustion were 0.8 thousand metric tons, up by 4 percent from 1998 levels but 13 percent below 1990 levels. While the share of waste burned is estimated to be unchanged between 1998 and 1999, total waste generated increased by 4 percent. The total volume of waste generated in the United States increased by 33 percent between 1990 and 1999; however, the share of waste burned in 1999 was just 7.5 percent, compared with 11.5 percent in 1990.⁴⁹

Human Sewage in Wastewater

Nitrous oxide is emitted from wastewater that contains nitrogen-based organic materials, such as those found in human or animal waste. It is produced by two natural processes: nitrification and denitrification. Nitrification, an aerobic process, converts ammonia into nitrate; denitrification, an anaerobic process, converts nitrate to nitrous oxide. Factors that influence the amount of nitrous oxide generated from wastewater include temperature, acidity, biochemical oxygen demand (BOD),⁵⁰ and nitrogen concentration.

In 1999, nitrous oxide emissions from wastewater were about 17.8 thousand metric tons, a 1-percent increase from 1998 levels and a 13-percent increase from the 1990 level (Table 24). Estimates of nitrous oxide emissions from human waste are scaled to population size and per

capita protein intake. U.S. population has grown by 9.3 percent since 1990. U.S. per capita protein intake rose steadily between 1990 and 1999, with a brief respite in 1995 and 1996. Today, U.S. per capita protein intake is 7.3 percent above 1990 levels. Data on protein intake are taken from the United Nations Food and Agriculture Organization (FAO).⁵¹

Industrial Processes

U.S. Nitrous Oxide Emissions from Industrial Processes, 1990-1999

Estimated 1999 Emissions (Thousand Metric Tons Nitrous Oxide)	56.6
Change Compared to 1998 (Thousand Metric Tons Nitrous Oxide)	-1.5
Change from 1998 (Percent)	-2.6%
Change Compared to 1990 (Thousand Metric Tons Nitrous Oxide)	-39.9
Change from 1990 (Percent)	-41.3%

Nitrous oxide is emitted as a byproduct of certain chemical production processes. Table 29 provides estimates of emissions from the production of adipic acid and nitric acid, the two principal known sources. Emissions from the combination of these two processes were 56.6 thousand metric tons in 1999, a decrease of 39.9 thousand metric tons (41 percent) since 1990 and 1.5 thousand metric tons (3 percent) since 1998. All of the decline can be traced to decreased emissions from adipic acid production.

Adipic Acid Production

Adipic acid is a fine white powder that is used primarily in the manufacture of nylon fibers and plastics, such as carpet yarn, clothing, and tire cord. Other uses of adipic acid include production of plasticizer for polyvinyl chloride and polyurethane resins, lubricants, insecticides, and dyes.

In the United States, three companies, which operate a total of four plants, manufacture adipic acid by oxidizing a ketone-alcohol mixture with nitric acid. Nitrous oxide is an intrinsic byproduct of this chemical reaction. For every metric ton of adipic acid produced, 0.3 metric ton of nitrous oxide is created.⁵² Between 1990 and 1994,

⁴⁹ "Nationwide Survey: The State of Garbage in America 1999," *Biocycle* (April 2000).

⁵⁰ Biochemical oxygen demand is a measure of the organic content within the wastewater that is subject to decomposition.

⁵¹ Food and Agriculture Organization of the United Nations, statistical databases, web site <http://apps.fao.org>.

⁵² M.H. Thieme and W.C. Troglor, "Nylon Production: An Unknown Source of Atmospheric Nitrous Oxide," *Science*, Vol. 251, No. 4996 (February 1991).

emissions from adipic acid manufacture grew by 18 percent, reaching 67.0 thousand metric tons (Table 29). After remaining relatively stable in 1995 and 1996, emissions dropped sharply to 12.1 thousand metric tons in 1998, and they remained at that level in 1999. Through 1996, two of the four plants that manufacture adipic acid controlled emissions by thermally decomposing the nitrous oxide. This technique eliminates 98 percent of potential emissions from the plants.⁵³

During the first quarter of 1997, a third plant installed emissions controls, increasing the share of adipic acid production employing emissions abatement controls from 74 percent in 1996 to 92 percent in 1997. With emissions controls in place for the full year, 97 percent of emissions from U.S. adipic acid production were controlled in 1998.⁵⁴ Estimated emissions of nitrous oxide from uncontrolled adipic acid production decreased from 21.8 thousand metric tons in 1997 to 6.9 thousand metric tons in 1999, and 1999 emissions of nitrous oxide from controlled plants remained relatively constant at 5.2 thousand metric tons. With the share of adipic acid production employing abatement controls now at

nearly 100 percent, future changes in nitrous oxide emissions from this source are expected to result primarily from changes in plant production levels in response to market demand.

Nitric Acid Production

Nitric acid, a primary ingredient in fertilizers, usually is manufactured by oxidizing ammonia (NH₃) with a platinum catalyst. Nitrous oxide emissions are a direct result of the oxidation. The 8,093.9 thousand metric tons of nitric acid manufactured in 1999 resulted in estimated emissions of 44.5 thousand metric tons of nitrous oxide (Table 29). This estimate was 4 percent lower than 1998 levels but 12 percent higher than 1990 levels. The emissions factor used to estimate nitrous oxide emissions from the production of nitric acid, was based on measurements at a single DuPont plant, which indicated an emissions factor of 2 to 9 grams of nitrous oxide emitted per kilogram of nitric acid manufactured, suggesting an uncertainty of plus or minus 75 percent in the emissions estimate.⁵⁵

⁵³Radian Corporation, *Nitrous Oxide Emissions From Adipic Acid Manufacturing* (Rochester, NY, January 1992), p. 10.

⁵⁴R.A. Reimer, R.A. Parrett, and C.S. Slaten, "Abatement of N₂O Emissions Produced in Adipic Acid," in *Proceedings of the Fifth International Workshop on Nitrous Oxide Emissions* (Tsukuba, Japan, July 1992).

⁵⁵Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.18, web site www.ipcc.ch/pub/guide.htm.

Nitrous Oxide Emissions

Table 24. Estimated U.S. Emissions of Nitrous Oxide, 1990-1999
(Thousand Metric Tons Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Energy Use										
Mobile Sources	166	176	186	195	209	222	217	221	223	228
Stationary Combustion	44	44	45	46	46	47	49	49	49	51
Total	211	220	231	240	255	269	266	269	272	279
Agriculture										
Nitrogen Fertilization of Soils	614	620	638	621	686	616	607	628	640	637
Crop Residue Burning	1	1	1	1	2	1	1	2	2	2
Solid Waste of Domesticated Animals	229	231	234	237	239	242	238	236	233	232
Total	844	853	873	860	927	859	846	865	874	870
Waste Management										
Waste Combustion	1	1	1	1	1	1	1	1	1	1
Human Sewage in Wastewater	16	16	16	16	17	17	17	17	18	18
Total	17	17	17	17	18	18	18	18	18	19
Industrial Sources	96	99	95	100	110	111	116	74	58	57
Total	1,168	1,189	1,217	1,218	1,310	1,257	1,246	1,226	1,223	1,224

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Emissions calculations based on Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.81-4.94, web site www.ipcc.ch/pub/guide.htm; and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

Table 25. U.S. Nitrous Oxide Emissions from Mobile Sources, 1990-1999
(Thousand Metric Tons Nitrous Oxide)

Item	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Motor Vehicles										
Passenger Cars	99	107	115	112	111	108	109	109	110	112
Buses	*	*	*	*	*	*	*	*	*	*
Motorcycles	*	*	*	*	*	*	*	*	*	*
Light-Duty Trucks	49	51	53	64	79	94	88	91	92	93
Other Trucks	6	6	6	6	7	7	7	8	8	8
Total	154	164	174	183	197	210	205	208	210	214
Other Mobile Sources	12	12	12	12	12	12	13	12	13	14
Total	166	176	186	195	209	222	217	221	223	228

*Less than 500 metric tons of nitrous oxide.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: Calculations based on vehicle miles traveled from U.S. Department of Transportation, *Federal Highway Statistics* (various years), Table VM-1. Passenger car and light-duty truck emissions coefficients from U.S. Environmental Protection Agency, Office of Air and Radiation, *Emissions of Nitrous Oxide From Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1996*, EPA-420-R-98-009 (Washington DC, August 1998). Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 1.64-1.68, web site www.ipcc.ch/pub/guide.htm.

Table 26. U.S. Nitrous Oxide Emissions from Stationary Combustion Sources, 1990-1999
(Thousand Metric Tons Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Residential										
Coal	*	*	*	*	*	*	*	*	*	*
Fuel Oil	1	1	1	1	1	1	1	1	1	1
Natural Gas	*	*	*	*	*	*	1	*	*	*
Wood	2	2	3	2	2	2	2	2	1	2
Commercial										
Coal	*	*	*	*	*	*	*	*	*	*
Fuel Oil	1	1	*	*	*	*	*	*	*	*
Natural Gas	*	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*	*
Industrial										
Coal	4	4	4	4	4	4	3	3	3	3
Fuel Oil	5	5	5	5	5	5	5	6	6	6
Natural Gas	1	1	1	1	1	1	1	1	1	1
Wood	6	6	6	6	7	7	7	7	8	9
Electric Utility										
Coal	23	23	23	24	24	24	26	27	27	27
Fuel Oil	1	1	1	1	1	*	*	*	1	1
Natural Gas	*	*	*	*	*	*	*	*	*	*
Wood	*	*	*	*	*	*	*	*	*	*
Fuel Totals										
Coal	27	27	27	28	28	28	29	30	30	30
Fuel Oil	7	7	7	7	7	7	7	7	7	8
Natural Gas	2	2	2	2	2	2	2	2	2	2
Wood	9	9	9	9	9	10	10	9	9	11
Total	44	44	45	46	46	47	49	49	49	51

*Less than 500 metric tons of nitrous oxide.

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: Emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.50, web site www.ipcc.ch/pub/guide.htm. Energy consumption data from Energy Information Administration, *State Energy Data Report 1997*, DOE/EIA-0214(97) (Washington, DC, September 1999); and *Monthly Energy Review*, DOE/EIA-0035(2000/08) (Washington, DC, August 2000).

Table 27. U.S. Nitrous Oxide Emissions from Nitrogen Fertilization of Agricultural Soils, 1990-1999
(Thousand Metric Tons Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Direct Emissions										
Nitrogen Fertilizers	179	182	183	193	195	173	159	159	161	162
Animal Manure	6	6	6	6	6	6	6	6	6	6
Crop Residues	92	90	104	83	112	93	106	113	116	113
Soil Mineralization	7	7	7	7	7	7	7	7	7	7
Biological Fixation in Crops.	198	201	203	190	222	210	212	224	232	230
Total	482	486	503	480	543	488	489	510	521	517
Indirect Emissions										
Soil Leaching	112	114	115	121	122	109	100	101	101	102
Atmospheric Deposition	19	20	20	21	21	19	17	17	17	18
Total	132	134	135	142	143	128	118	118	119	120
Total	614	620	638	621	686	616	607	628	640	637

P = preliminary data.

Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.89-4.107, web site www.ipcc.ch/pub/guide.htm. Total nitrogen content of U.S. commercial fertilizer consumption—1988-1994, Tennessee Valley Authority; 1995-1999, Association of American Plant Food Control Officials, *Commercial Fertilizers* (Washington, DC, various years). Manure application based on cattle population data provided by the U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock, Dairy and Poultry Service. Typical animal sizes from U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993). Manure production and waste management systems used from L.M. Safley, M.E. Casada et al., *Global Methane Emissions From Livestock and Poultry Manure* (Washington, DC, February 1992), and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

Table 28. U.S. Nitrous Oxide Emissions from Solid Waste of Domesticated Animals, 1990-1999
(Thousand Metric Tons Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Cattle	215	217	219	223	225	228	224	221	218	218
Swine	5	5	5	5	6	5	5	6	6	6
Poultry	3	3	3	4	4	4	4	4	4	4
Sheep	3	3	3	3	3	3	3	2	2	2
Goats.	1	1	1	1	1	1	1	1	1	1
Horses	1	1	1	1	1	1	1	1	1	1
Total	229	231	234	237	239	242	238	236	233	232

P = preliminary data.

Note: Totals may not equal sum of components due to independent rounding.

Sources: Estimates presented in this chapter. Nitrogen content of waste by species, manure management systems, and emissions coefficients from Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.89-4.107, web site www.ipcc.ch/pub/guide.htm. Animal populations from U.S. Department of Agriculture, National Agricultural Statistics Service, web sites www.usda.gov/nass/pubs/histdata.htm and www.nass.usda.gov/ipedb/.

Table 29. U.S. Nitrous Oxide Emissions from Industrial Processes, 1990-1999
(Thousand Metric Tons Nitrous Oxide)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Adipic Acid										
Controlled Sources	3	4	3	3	4	4	4	5	5	5
Uncontrolled Sources.	54	56	52	56	63	63	66	22	7	7
Adipic Acid Subtotal.	57	60	55	59	67	67	70	27	12	12
Nitric Acid	40	40	41	41	43	44	46	47	46	45
Total Known Industrial Sources	96	99	95	100	110	111	116	74	58	57

P = preliminary data.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98) (Washington, DC, October 1999). Totals may not equal sum of components due to independent rounding.

Sources: Data sources and methods documented in Appendix A.

5. Other Gases: Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride

Overview

Total U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Carbon Equivalent)	37.6
Change Compared to 1998 (Million Metric Tons Carbon Equivalent)	-2.2
Change from 1998 (Percent)	-5.4%
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	13.6
Change from 1990 (Percent)	56.8%

In addition to the three principal gases (carbon dioxide, methane, and nitrous oxide), there are other gases that account for 2 percent of U.S. greenhouse gas emissions when weighted by global warming potential (GWP). These gases are engineered chemicals that do not occur in nature. Although they tend to have very high GWPs, they are emitted in such small quantities that their overall impact is currently small.

The Kyoto Protocol has defined three classes of these gases that “count” for emissions estimation: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆). This chapter describes emissions sources and gives emissions estimates for HFCs, PFCs, and SF₆.

As a group, emissions of HFCs, PFCs, and SF₆ are rising. In the case of HFCs, the rise in emissions reflects the introduction of HFCs specifically as replacements for CFCs, whose use is being phased out under the Montreal Protocol because they damage the Earth’s ozone

layer. CFCs have been widely used as refrigerants, aerosol propellants, and foam blowing agents for many years, but with CFC production virtually ceasing by 1996, HFCs have been introduced into the market to fill the void in many key applications. Emissions of PFCs and perfluoropolyethers (PFPEs) have also been rising in the 1990s (although not as rapidly as HFC emissions), mainly because of the recent commercial introduction of new PFCs and PFPEs both as CFC substitutes and for use in various applications in the semiconductor manufacturing industry.

HFCs, PFCs, and SF₆ are emitted in small quantities, but they have disproportionate effects because their long atmospheric lifetimes and extreme scarcity in the atmosphere give them extremely large GWPs. SF₆ is the most potent of the greenhouse gases, with a GWP of 23,900. PFCs also tend to have particularly high GWPs, falling in the range of 7,000 to 9,000. Among HFCs, HFC-23 is the most potent greenhouse gas, with a GWP of 11,700.

Table 30 summarizes U.S. emissions of HFCs, PFCs, and SF₆ from 1990 to 1999, and Table 31 shows the corresponding emissions in million metric tons carbon equivalent. Throughout the 1990s, HFC emissions have accounted for roughly one-half of the total carbon-equivalent emissions of HFCs, PFCs, and SF₆ combined.

The emissions estimates presented in Tables 30 and 31 are taken primarily from the EPA report, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*.⁵⁶ The 1999 preliminary estimates represent advance estimates developed by EPA and provided to EIA.⁵⁷ The advance EPA estimates also included some relatively minor revisions to the historical emissions for HFCs, based on more recent runs of EPA’s Vintaging Model. The revisions to the historical estimates are reflected in the emissions estimates presented in this chapter.⁵⁸

⁵⁶U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), Chapter 3, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

⁵⁷E-mail correspondence with the U.S. Environmental Protection Agency’s Climate Protection Division on August 29, 2000, and with EPA’s contractor, ICF Inc., on August 30, 2000.

⁵⁸More information on methodologies and data sources for emissions of halocarbons and related gases is provided in Appendix A, “Estimation Methods,” web site www.eia.doe.gov/oiaf/1605/ggrrpt/index.html.

What's New in This Chapter

HFCs, PFCs, and SF₆. The primary source for the emission estimates presented in this chapter is the annual greenhouse gas emissions inventory prepared by the U.S. Environmental Protection Agency (EPA). The EPA inventory for 2000,^a which includes emissions estimates through 1998, incorporates a number of changes to the estimates of HFC, PFC, and SF₆ emissions before 1998. Those changes are reflected in the emissions estimates presented in this chapter.

The changes to the historical emissions estimates are the result of revisions to the data and estimation methodologies used by EPA. Three sets of revisions were made:

- Based on a review of trends in ozone-depleting substance substitutions, the EPA updated the assumptions used in its Vintaging Model for stationary refrigeration and foam blowing. The Vintaging Model is used by EPA to estimate emissions of gases used as substitutes for ozone-depleting substances (which are being phased out pursuant to the Montreal Protocol). The updates result in an average decrease of 22.7 percent in aggregate carbon-equivalent HFC, PFC, and SF₆ emissions from substitution of ozone-depleting substances for 1994 through 1997.
- PFC emissions from aluminum production for 1990 through 1997 were recomputed using a revised methodology that combines smelter-specific data on the frequency and duration of anode effects with coefficients that relate these parameters to PFC emissions. The methodological revisions resulted in an average increase of 8.3 percent in 1990-1997 PFC emissions from aluminum production.
- In past inventories, emissions from the semiconductor industry were estimated on the basis of gas sales data for 1994, combined with emissions factors for the main gases, semiconductor sales growth projections, and estimates of the effectiveness of emission reduction efforts. This year, the estimation methodology was revised to make use of two sets of data. For 1990 through 1994, emissions were reestimated based on historical silicon production, the estimated average number of interconnecting layers in the chips produced, and

an estimated per-layer emission factor. For 1995 through 1998, emissions were estimated on the basis of emissions data reported by participants in EPA's PFC Emission Reduction Partnership for the Semiconductor Industry. These methodological revisions resulted in an average 72.4-percent increase in annual HFC, PFC, and SF₆ emissions from semiconductor manufacture for 1990-1997.

Historical emissions for a group of gases including HFC-152a, HFC-227ea, HFC-4310mee, and a variety of PFCs and perfluoropolyethers (PFPEs) have been revised. Emissions of these substances are considered confidential by EPA and are published only in total for the group as a whole, in metric ton carbon equivalent units. Last year, emissions of each of these substances were estimated by EIA, based on extrapolation of trends shown in earlier published estimates. This year, EIA has adopted the EPA's emissions estimates for this group of substances. The new estimates have the effect of reducing overall carbon-equivalent emissions of HFCs and PFCs by approximately 9 percent from 1995 to 1999, and by smaller amounts prior to 1995.

Ozone-Depleting Substances and Criteria Pollutants. In previous years, this chapter included emissions estimates, and accompanying discussions, of a variety of gases that have ambiguous effects on climate, including ozone-depleting substances—chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and bromofluorocarbons (halons). This chapter also covered the criteria pollutants—carbon monoxide (CO), nitrogen oxides (NO_x), and nonmethane volatile organic compounds (NMVOCs)—which have indirect effects on climate through their effects on atmospheric concentrations of greenhouse gases. This year, emissions estimates for those gases are not included in this chapter, because the ozone-depleting substances and criteria pollutants were excluded from the Kyoto Protocol. Furthermore, production of the ozone-depleting gases is being phased out under the Montreal Protocol. As a result, HFCs are being used to replace CFCs and HCFCs in a wide variety of applications. Although no longer included in the main body of this report, emissions estimates for ozone-depleting substances and criteria pollutants are included in Appendix D, "Emissions Sources Excluded."^b

^aU.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

^bThe appendixes for this report are available on web site www.eia.doe.gov/oiaf/1605/ggrpt/index.html.

Hydrofluorocarbons (HFCs)

U.S. Emissions of Hydrofluorocarbons, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Carbon Equivalent)	21.2
Change Compared to 1998 (Million Metric Tons Carbon Equivalent)	-0.8
Change from 1998 (Percent)	-3.8%
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	11.4
Change from 1990 (Percent)	116.6%

HFCs are compounds containing carbon, hydrogen, and fluorine. They do not destroy ozone. The market for HFCs is expanding as CFCs are being phased out. It is difficult to keep pace with the variety of HFCs that are being developed and the quantities being produced. Consequently, accurate data are difficult to obtain.

HFC-23

Although emissions of HFC-23 are relatively small, its high GWP gives it a substantial direct effect. HFC-23 is created as a byproduct in the production of HCFC-22. Small amounts are also used in semiconductor manufacture and as a fire-extinguishing agent.

EPA estimates 1998 HFC-23 emissions at 3,420 metric tons.⁵⁹ Annual emissions dropped by 23 percent between 1992 and 1995 but increased by 49 percent between 1995 and 1998. Consumption of HCFC-22 continues to grow, although at a slower rate than in past years. It continues to dominate the refrigerant market for stationary refrigeration and air conditioning (including chillers, room air conditioners, and dehumidifiers).⁶⁰ Because of the strong demand, capacity utilization of HCFC-22 production facilities worldwide is estimated at 94 percent.⁶¹

The Clinton Administration's Climate Change Action Plan (CCAP) includes a voluntary program with HCFC-22 producers to reduce HFC-23 emissions, which

may help to offset the rising demand for HCFC-22 in the short term. In the longer term, EPA intends to restrict domestic HCFC-22 production by 2010 and to phase out U.S. production entirely, pursuant to U.S. agreements under the Copenhagen Amendments to the Montreal Protocol.⁶² This will automatically reduce and eventually eliminate HFC-23 emissions from this source.

1,2,2,2-Tetrafluoroethane (HFC-134a)

HFC-134a, with a GWP of 1,300, is gaining importance as a replacement for CFCs, especially in automotive air conditioners. Emissions in 1990 were estimated at 560 metric tons, but since then they have grown rapidly to 26,850 metric tons in 1998 (Table 30). In 1993, Ford Motor Company sold nearly 40,000 vehicles that used HFC-134a as the air conditioner coolant. Each vehicle used about 2 pounds of coolant.⁶³ Previous models used about 2.5 pounds of CFC-12. Nearly all 1994 and subsequent model year automobiles use HFC-134a as their air conditioner refrigerant. In addition, HFC-134a conversion packages are now available for older cars.

Automobile air conditioners are subject to leakage, with sufficient refrigerant leaking (15 to 30 percent of the charge) over a 5-year period to require servicing. On its Form EIA-1605, General Motors (GM) reported total HFC-134a emissions of about 2,150 metric tons from GM-made vehicles on the road in 1998.⁶⁴ GM based its estimate on an assumed annual leakage rate of 10 percent per year. With GM vehicles accounting for about one-third of the U.S. light-duty fleet,⁶⁵ the GM emissions estimate implies that total U.S. HFC-134a emissions from mobile air conditioners were equal to about 6,500 metric tons in 1998. Emissions from this source are expected to continue to increase in the near future, as the replacement of vehicles using CFCs proceeds at a rapid pace.

In addition to its use in all new automobiles, an automotive aftermarket for HFC-134a has been developing. Spurred by rising prices for CFC-12, 5 million cars were retrofitted for HFC-134a use in 1997.⁶⁶ This trend toward retrofitting is expected to continue, given that CFC-12 is no longer produced, remaining inventories are being depleted, and CFC-12 prices are rising.⁶⁷ Furthermore, many of the air conditioners in mid-1990s models

⁵⁹U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), Chapter 3, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

⁶⁰C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

⁶¹J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

⁶²See web site www.epa.gov/ozone/index.html.

⁶³Information obtained by oral communication with Ford Motor Company representatives.

⁶⁴Form EIA-1605 is a greenhouse gas emissions and emissions reductions reporting form, which is submitted to EIA on a voluntary basis by entities interested in creating a public record of their emissions reduction activities.

⁶⁵American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures 96* (Detroit, MI, 1999).

⁶⁶"Fluorocarbon Outlook Turns Bullish," *Chemical Market Reporter* (May 25, 1998).

⁶⁷J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

(which were among the first automobiles to use HFC-134a) are now due to be serviced. A spokesperson for Elf Atochem North America estimates the U.S. aftermarket for HFC-134a at 45 to 50 million pounds, or roughly 35 percent of total annual demand. He believes that, as the market for HFC-134a matures, the aftermarket will eventually be about twice the size of the original equipment market.⁶⁸ The automotive aftermarket is already responsible for much of the growth in current HFC-134a demand.⁶⁹

HFC-134a is also used as a refrigerant in most new refrigerators built in the United States and in commercial chillers, but leakage from these sources is much less than from automotive air conditioners. Leakage occurs primarily during servicing of the units rather than during normal operation. Short-term uses of HFC-134a, on the other hand, are becoming an important source of emissions. Such uses include aerosols and open-cell foam blowing, which are denoted as short term because most of the HFC-134a used will be emitted to the atmosphere within a short period of time. According to the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), worldwide sales of HFC-134a for short-term applications jumped almost fourfold between 1994 and 1995. However, sales for short-term uses leveled off at 10,000 metric tons in 1996 and then dropped to 7,400 metric tons (or 7 percent of sales for all uses) in 1997. A further drop, to 6,500 metric tons, occurred in 1998.⁷⁰ New developments in the U.S. market may, however, reverse this recent downward trend.

Beginning in September 1998, U.S. regulations require aerosol manufacturers to use propellants with a maximum volatile organic compound (VOC) level of 45 to 55 percent. HFC-134a is one of only two chemicals that meet this requirement (the other being HFC-152a). Also, in January 1999, the major marketers of tire inflaters began requiring the use of nonflammable material, creating additional demand for HFC-134a. Pennzoil was the first company to enter this new market, after removing its hydrocarbon-based canisters and reconfiguring them to use HFC-134a.⁷¹

For many years, the HFC-134a market was characterized by excess capacity and low prices, because the transition away from CFC-12 occurred more slowly than producers had expected.⁷² In 1998 and 1999, however, the market tightened considerably, as evidenced by a series of price increases. Driven in part by a demand surge

triggered by an unusually hot summer in 1999, prices nearly doubled, rising from a low of \$1.50 per pound to \$2.50 per pound by September 1999. For the rest of 1999 and the first half of 2000, the market stabilized, with only one minor price increase in early 2000.

A number of HFC-134a producers are undertaking modest capacity expansion projects, including DuPont, ICI Klea, and Honeywell (formerly AlliedSignal). More significant additions of new capacity are likely to be needed, however, given that capacity is increasing by only 2 to 3 percent per year, while global demand is growing by 10 percent. SRI International predicts that global demand will reach 20 million pounds by 2001; and according to a representative of Elf Atochem, the market will face significant supply shortages unless more investment in new capacity is undertaken over the next several years.⁷³ The required capacity will presumably be built, but it is possible that the expansion in supply will lag behind the growth in demand. Anticipating and planning for demand growth has proven to be a difficult challenge for producers, who must manage as best as possible an unprecedented transition from an established product (CFC-12) that is now under a global ban to a new product (HFC-134a). In the long term, consumption and emissions of HFC-134a are expected to continue rising rapidly, although it is possible that capacity constraints may act as a brake on consumption in the near term.

1,1-Difluoroethane (HFC-152a)

As a non-ozone-depleting substance with a GWP of 140, HFC-152a is an attractive potential replacement for CFCs. It can be used as a blowing agent, an ingredient in refrigerant blends (e.g., in R-500), and in fluoropolymer manufacturing applications. There are no HFC-152a emissions associated with the latter application, because the HFC-152a is consumed in the manufacturing process. In 1996, 5 million pounds of HFC-152a was consumed in fluoropolymer manufacturing.⁷⁴ HFC-152a is also compatible with the components used in aerosol products. Unlike CFCs, however, HFC-152a is flammable.

Only one U.S. company (DuPont) produces HFC-152a, using the trade name Dymel-152a. DuPont probably was producing HFC-152a at nearly full capacity in 1994, corresponding to production of about 8,000 metric tons. In 1995 the company reported having doubled its

⁶⁸"HFC-134a Prices Rise As Market Tightens," *Chemical Market Reporter* (March 15, 1999).

⁶⁹J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

⁷⁰Alternative Fluorocarbons Environmental Acceptability Study, *Production, Sales and Atmospheric Release of Fluorocarbons Through 1998*, web site www.afeas.org/prodsales_download.html.

⁷¹J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

⁷²C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

⁷³J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

⁷⁴C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

production capacity from 1992 levels, to 15,875 metric tons.⁷⁵ The company reported 1994 HFC-152a emissions of 180 metric tons on its Form EIA-1605 indicating fugitive emissions during production of 2.3 percent. By 1997, however, DuPont's reported emissions dropped to only 36 metric tons.

Other HFCs

Other HFCs with considerable radiative forcing potential include HFC-125 (C₂H₅F₅), HFC-143a (C₂H₃F₃), HFC-227ea (C₃H₇F₇), and HFC-236fa (C₃H₂F₆), with 100-year GWPs of 2,800, 3,800, 2,900, and 6,300, respectively. The EPA estimates 1998 emissions of HFC-125 at 1,120 metric tons and of HFC-143a at 490 metric tons. Emissions of these HFCs are small but growing rapidly, as they continue to find applications as substitutes for CFCs.

HFC-125 is used in the blend R-410A, which is designed to replace HCFC-22 as the refrigerant of choice for stationary refrigeration and air conditioning applications. Some manufacturers have already introduced air conditioners that use R-410A, but as yet the product has captured only 2 percent of the market. As the phaseout of HCFC-22 begins to gain momentum, however, Honeywell expects a rapid increase in the demand for R-410A.⁷⁶ HFC-236fa is also used as a refrigerant, in particular by the U.S. Navy for shipboard applications.⁷⁷ Other HFCs and HFC blends are also likely to gain market share as a result of the phaseout, because no single product is suited for all applications. For example, each potential replacement product has an optimal operating temperature range; hence, the refrigerant best suited for use in ice cream freezers will differ from the best choice for milk coolers.⁷⁸

In addition to replacing HCFC-22 in stationary air conditioning and refrigeration applications, HFCs are expected to gain new markets as foam blowing agents. CFCs have already been phased out of this market, having been replaced by HCFCs (primarily HCFC-141b). However, HCFCs are to be banned as foam blowing agents by 2003 under the Montreal Protocol. Among the potential replacements, HFC-245fa appears to be the strongest contender at present.⁷⁹

Honeywell is building a world-scale plant in Louisiana for the production of HFC-245fa, which will become fully operational by 2002. Semi-commercial quantities of

the product will be available from the plant in 2000. Honeywell is also considering the possibility of building a second HFC-245fa plant overseas, to serve the European and Asian markets,⁸⁰ and is developing blends that combine HFC-245fa with other materials to enhance its cost/performance ratio. To date, however, the foam blowing industry has failed to signal a clear preference for HFC-245fa or other alternatives. Instead, it continues to rely primarily on HCFC-141b while waiting to see which of the possible replacement candidates emerges as the preferred alternative.⁸¹ For some applications, non-fluorochemical alternatives (e.g., hydrocarbons) have been identified.⁸²

Perfluorocarbons (PFCs)

U.S. Emissions of Perfluorocarbons, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Carbon Equivalent)	4.9
Change Compared to 1998 (Million Metric Tons Carbon Equivalent)	-0.2
Change from 1998 (Percent)	-4.2%
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	-1.6
Change from 1990 (Percent)	-25.1%

Perfluorocarbons are compounds composed of carbon and fluorine. PFC emissions are not regulated, although their high GWPs (6,500 for perfluoromethane and 9,200 for perfluoroethane) have drawn the attention of the CCAP. PFCs are also characterized by long atmospheric lifetimes (up to 50,000 years); hence, unlike HFCs, they are essentially permanent additions to the atmosphere. As byproducts of aluminum production, they arise during discrete periods of process inefficiency. Emissions can be reduced by improving process efficiency. The Voluntary Aluminum Industrial Partnership, aimed at reducing PFC emissions from the aluminum industry, is a CCAP initiative.

The principal quantifiable source of PFCs is as a byproduct of aluminum smelting. The EPA estimates U.S. emissions from aluminum production at 1,420 metric tons of perfluoromethane and 120 metric tons of

⁷⁵ "DuPont Set To Expand Markets for Ozone-Safe HFC-152a Product," *Ozone Depletion Online Today* (Alexandria, VA, June 9, 1995).

⁷⁶ J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

⁷⁷ E-mail correspondence with the U.S. Department of Energy's Office of Policy, October 18, 2000.

⁷⁸ C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

⁷⁹ C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

⁸⁰ J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

⁸¹ C. Boswell, "Hydrofluorocarbons Build with Transition Away from CFCs," *Chemical Market Reporter* (September 13, 1999).

⁸² J. Ouellette, "Fluorocarbon Market Is Poised To Grow," *Chemical Market Reporter* (June 19, 2000).

perfluoroethane in 1998. U.S. primary aluminum production has been increasing since 1994, and the trend is expected to continue as the automobile industry expands its use of aluminum.⁸³

Another source of PFC emissions is semiconductor manufacturing. Perfluoromethane and perfluoroethane are used as etchants and cleaning agents in semiconductor manufacturing. The United States consumed an estimated 800 tons of perfluoroethane and perfluoromethane in 1995.⁸⁴ For 1998, the EPA estimates total emissions of all greenhouse gases from semiconductor manufacturing at 2.1 million metric tons carbon equivalent.⁸⁵

It is difficult to assess trends in PFC emissions from the semiconductor industry. On the one hand, the continued rapid expansion of the worldwide semiconductor market may lead to increased PFC use and emissions. On the other hand, industry efforts to curb emissions may help to offset these market forces to some extent.

A number of semiconductor manufacturing firms have joined an EPA program to reduce PFC emissions voluntarily.⁸⁶ In 1999, the World Semiconductor Council, comprising manufacturers from Europe, the United States, Japan, Taiwan, and South Korea, voluntarily committed to reduce emissions of PFCs by 10 percent from 1995 levels. In addition, a number of PFC distributors are developing PFC emissions control equipment.⁸⁷ Abatement and other control options are commercially available, and substitute chemicals that result in reduced emissions are being adopted.⁸⁸

A variety of other perfluorinated compounds are beginning to be used in the semiconductor industry, including C₃F₈ (manufactured by 3M), C₄F₁₀ (with a GWP of 7,000), C₆F₁₄ (with a GWP of 7,400), NF₃ (manufactured by Air Products), and CHF₃.

Sulfur Hexafluoride (SF₆)

U.S. Emissions of Sulfur Hexafluoride, 1990-1999

Estimated 1999 Emissions (Million Metric Tons Carbon Equivalent)	8.9
Change Compared to 1998 (Million Metric Tons Carbon Equivalent)	-1.3
Change from 1998 (Percent)	-12.7%
Change Compared to 1990 (Million Metric Tons Carbon Equivalent)	1.4
Change from 1990 (Percent)	18.1%

SF₆ is used as an insulator for circuit breakers, switch gear, and other electrical equipment. In addition, its extremely low atmospheric concentration makes it a useful atmospheric tracer gas for a variety of experimental purposes. It is also a fugitive emission from certain semiconductor manufacturing processes, and it is used as a cover gas during magnesium production and processing, to prevent the violent oxidation of molten magnesium in the presence of air.

SF₆ has a high GWP of 23,900, but it is not emitted in large quantities. The EPA's estimates indicate a gradual increase in U.S. emissions between 1990 and 1995, from 1,160 metric tons to 1,570 metric tons. Between 1995 and 1998 emissions held steady at 1,570 metric tons.⁸⁹

⁸³U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), p. 3-26, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

⁸⁴"PFCs Can Be Recycled with New Technology," American Institute of Chemical Engineers, Press Release (March 12, 1997).

⁸⁵U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), p. 3-32, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

⁸⁶"Environmental Protection Drives Emissions Reduction Effort," *Electronic Design* (December 1, 1997).

⁸⁷"EPA Launches PFC Reduction Program," *Chemical Week* (July 31, 1996). Without emissions control efforts, PFC emissions would be expected to rise as the use of PFCs in the semiconductor industry increases.

⁸⁸E-mail correspondence with the U.S. Environmental Protection Agency's Climate Protection Division, October 18, 2000.

⁸⁹U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), p. 3-32, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

Table 30. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-1999
(Thousand Metric Tons of Gas)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Hydrofluorocarbons										
HFC-23	3.0	2.6	3.0	2.7	2.7	2.3	2.7	2.6	3.4	2.6
HFC-134a	0.6	0.6	0.6	2.9	6.3	14.3	19.0	23.5	26.9	30.3
HFC-152a	W	W	W	W	W	W	W	W	W	W
HFC-125	*	*	0.2	0.5	0.3	0.5	0.7	0.9	1.1	1.3
HFC-227ea	W	W	W	W	W	W	W	W	W	W
HFC-143a	*	*	*	*	0.1	0.1	0.2	0.3	0.5	0.7
HFC-4310mee	W	W	W	W	W	W	W	W	W	W
HFC-236fa	*	*	*	*	*	*	*	*	0.1	0.2
Perfluorocarbons										
CF ₄	2.8	2.5	2.3	2.1	1.8	1.9	2.0	1.9	1.8	1.7
C ₂ F ₆	0.5	0.5	0.4	0.4	0.4	0.5	0.6	0.6	0.7	0.7
C ₄ F ₁₀	*	*	*	*	*	*	*	*	*	*
PFCs/PFPEs	W	W	W	W	W	W	W	W	W	W
Sulfur Hexafluoride	1.2	1.2	1.3	1.4	1.4	1.6	1.6	1.6	1.6	1.4

*Less than 50 metric tons of gas.

P = preliminary data. W = withheld to avoid disclosure of confidential data.

Note: Totals may not equal sum of components due to independent rounding.

Sources: **1990-1998**: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), p. 3-32, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html. **1999**: EIA estimates.

Other Gases

Table 31. U.S. Emissions of Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride, 1990-1999
(Million Metric Tons Carbon Equivalent)

Gas	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Hydrofluorocarbons										
HFC-23	9.57	8.30	9.57	8.62	8.62	7.34	8.62	8.33	10.91	8.36
HFC-134a	0.20	0.22	0.22	1.02	2.23	5.08	6.72	8.32	9.52	10.76
HFC-125	*	*	0.18	0.37	0.23	0.37	0.51	0.68	0.86	0.99
HFC-143a	*	*	*	0.01	0.05	0.11	0.22	0.34	0.51	0.70
HFC-236fa	*	*	*	*	*	*	*	0.03	0.21	0.36
Total	9.77	8.52	9.98	10.01	11.12	12.90	16.07	17.71	22.00	21.17
Perfluorocarbons										
CF ₄	5.33	4.67	4.40	3.91	3.35	3.50	3.71	3.50	3.44	3.26
C ₂ F ₆	1.23	1.13	1.10	1.10	1.10	1.33	1.58	1.56	1.68	1.66
C ₄ F ₁₀	*	*	*	*	*	*	*	*	*	*
Total	6.56	5.80	5.51	5.02	4.45	4.83	5.29	5.06	5.12	4.91
Other HFCs, PFCs/PFPEs	0.10	*	*	*	0.20	1.00	1.80	2.10	2.40	2.60
Sulfur Hexafluoride	7.56	7.82	8.15	9.06	9.32	10.23	10.23	10.23	10.23	8.93
Total Emissions	23.99	22.14	23.63	24.09	25.10	28.97	33.39	35.10	39.76	37.61

*Less than 50,000 metric tons carbon equivalent.

P = preliminary data.

Notes: Other HFCs, PFCs/PFPEs include HFC-152a, HFC-227ea, HFC-4310mee, and a variety of PFCs and perfluoropolyethers (PFPEs). They are grouped together to protect confidential data. Totals may not equal sum of components due to independent rounding.

Sources: **1990-1998:** U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), p. 3-32, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html. **1999:** EIA estimates. Global warming potentials used to convert emissions to carbon-equivalent basis from Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996), pp. 119 and 121.

6. Land Use Issues

Overview

Land use change and forestry issues are important to national and global inventories of greenhouse gases in two ways:

- Vegetation can “sequester” or remove carbon dioxide from the atmosphere and store it for potentially long periods in above- and below-ground biomass, as well as in soils. Soils, trees, crops, and other plants may make significant contributions to reducing net greenhouse gas emissions by serving as carbon “sinks.”
- Humans can alter the biosphere through changes in land use and forest management practices and, in effect, alter the quantities of atmospheric and terrestrial carbon stocks, as well as the natural carbon flux among biomass, soils, and the atmosphere.

Land use issues are of particular interest to the United States because U.S. forests and soils annually sequester large amounts of carbon dioxide. Much of the forest land in the United States was cleared for agriculture, lumber, or fuel in the hundred years prior to 1920. Since then, much agricultural and pastureland has reverted to forest land and is now covered with relatively young, rapidly growing trees.

The amount of carbon being sequestered annually is uncertain, in part because of an absence of data and because of difficulties in measuring sequestration. Moreover, in addition to technical uncertainties, there is also policy or accounting ambiguity about which aspects of the biological carbon cycle ought to be included in national inventories as anthropogenic emissions and removals.

The revised guidelines for national emissions inventories published in 1997 by the Intergovernmental Panel on Climate Change (IPCC) pursuant to the Framework Convention on Climate Change contain a set of rules governing the inclusion of carbon sequestration and land use in national inventories.⁹⁰ The U.S. Environmental Protection Agency (EPA), relying heavily on the work of U.S. Forest Service researchers Richard Birdsey and Linda Heath, estimates annual U.S. carbon

sequestration (generally defined according to the IPCC guidelines) at 211 million metric tons carbon equivalent (Table 32).⁹¹ Under the IPCC guidelines, this quantity would be treated as an offset to gross greenhouse gas emissions from other sources.

EPA’s carbon flux estimates are based on surveys of U.S. forest lands carried out at 5-year intervals by the U.S. Forest Service, U.S. Department of Agriculture. Annual estimates of carbon fluxes between survey years are interpolated and, therefore, change little from year to year, except when a new assessment is made.

In this year’s report, for the first time, landfilled yard trimmings are included in the EPA’s carbon flux estimates. The estimates for carbon fluxes from landfilled yard trimmings trend downward over time, based on EPA projections.

Total forestry carbon fluxes have fallen from 316 million metric tons carbon equivalent in 1990 to 211 million metric tons carbon equivalent in 1998. The decrease is due mainly to maturation and slowing in the spread of forest cover, as well as a reduction in landfilled yard trimmings. The dramatic drop between 1992 and 1993 is due, in part, to methodological changes that incorporated periodic activity data rather than annual stock estimates. As can be seen from the estimates, the vast majority of the carbon fluxes are from forests and soil (171 million metric tons carbon equivalent or 81 percent of total forestry carbon fluxes), followed by harvested wood (37 million metric tons carbon equivalent or 18 percent) and landfilled trimmings (2.3 million metric tons carbon equivalent or 1 percent).

To put these figures in perspective, carbon fluxes from forestry offset 14.1 percent of energy-related carbon dioxide emissions, which totaled 1,495 million metric tons carbon equivalent in 1998. The 211 million metric tons carbon equivalent sequestered through land use and forestry activities in 1998 would also act to offset total U.S. emissions of greenhouse gases by 11.6 percent. If the EPA’s estimate of 211 million metric tons carbon equivalent sequestered through carbon fluxes from forestry holds for 1999, then sequestration will offset a little less than 14 percent of the 1,511 million metric tons of

⁹⁰Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), web site www.ipcc.ch/pub/guide.htm.

⁹¹U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), p. 6-2, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

Table 32. Net Carbon Flux from Land Use Change and Forestry, 1990-1998
(Million Metric Tons Carbon Equivalent)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998
Forests									
Trees	95.6	95.6	95.6	74.0	74.0	74.0	74.0	74.0	74.0
Understory	2.4	2.4	2.4	1.3	1.3	1.3	1.3	1.3	1.3
Forest Floor	20.8	20.8	20.8	9.8	9.8	9.8	9.8	9.8	9.8
Soil	155.2	155.2	155.2	86.3	86.3	86.3	86.3	86.3	86.3
Total Forests	274.2	274.2	274.2	171.3	171.3	171.3	171.3	171.3	171.3
Harvested Wood									
Wood Products	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9
Landfilled Wood	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4
Total Harvested Wood . . .	37.3								
Landfilled Yard Trimmings . .	4.9	4.8	4.7	4.2	3.7	3.3	2.7	2.6	2.3
Total Net Flux	316.4	316.1	316.2	213.3	212.8	211.9	211.3	211.2	210.9

Source: U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, EPA-236-R-00-001 (Washington, DC, April 2000), p. 6-2, web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html, drawing on the work of Richard Birdsey and Linda Heath of the U.S. Forest Service.

carbon dioxide emitted through the burning of fossil fuels in 1999.

Land Use and the Kyoto Protocol

The United States and many other countries participating in the Kyoto Protocol believed that it was important to include Land Use, Land Use Change and Forestry (LULUCF) activities in a binding treaty limiting greenhouse gas emissions; however, the issues of whether and how terrestrial carbon sequestration would be accepted for meeting commitments were the subject of complex and difficult negotiations at Kyoto. While LULUCF activities were ultimately included in the Kyoto Protocol, controversial issues in its implementation remain.⁹²

Under Article 3 of the Kyoto Protocol, countries must count both sequestration and emissions from a limited set of LULUCF activities toward meeting their Kyoto Protocol target commitments. Parties must identify and examine all activities that release a greenhouse gas into the atmosphere (a source) and enhance reservoirs that sequester carbon (sinks).⁹³

Articles 3.3, 3.4, and 3.7 provide the framework for the accounting of sources and sinks for compliance purposes under the Kyoto Protocol:

- Under Article 3.3, permissible sink activities are defined as “. . . direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation (ARD), since 1990.” However, a limited accounting system is prescribed for land-use change and forestry activities, as they are not included in the source categories listed in Annex A of the Protocol for calculating the “aggregate anthropogenic carbon dioxide equivalent emissions” (Article 3.1). Emissions and sequestration resulting from LULUCF activities are not included in the 1990 emissions baseline, but specified terrestrial emissions and removals may be used to meet commitments within the first commitment period (2008-2012).
- Article 3.4 of the Kyoto Protocol details a process for including additional LULUCF activities that developed country Parties may apply in the first commitment period and must apply in the second and subsequent commitment periods, provided that activities have taken place since 1990.⁹⁴ Further,

⁹²G. Marland and B. Schlamadinger, *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol* (Arlington, VA: Pew Center on Global Climate Change, June 2000), p. 15, web site www.pewclimate.org/projects/land_use.cfm.

⁹³Australian Greenhouse Office, *Greenhouse Sinks and the Kyoto Protocol: An Issues Paper* (Canberra, Australia: Commonwealth of Australia, February 2000), p. 2, web site www.greenhouse.gov.au/pubs/internationalsinks/.

⁹⁴G. Marland and B. Schlamadinger, *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol* (Arlington, VA: Pew Center on Global Climate Change, June 2000), p. 16, web site www.pewclimate.org/projects/land_use.cfm.

Article 3.4 calls for every Party to “. . . establish its level of carbon stocks in 1990 and to enable an estimate to be made of its changes in carbon stocks in subsequent years.”⁹⁵

- Article 3.7 describes special accounting rules, namely a “limited net-net approach,” for countries for which LULUCF was a net source of emissions in the 1990 base year. This rule was introduced by and applies primarily to Australia.⁹⁶ Thus, Article 3.7 allows Australia to include emissions from land clearing in 1990 in the baseline for the calculation of its assigned amount.⁹⁷

Implementation of these articles is complicated by a lack of clear definitions for words such as “reforestation” and “forest.” Further, the LULUCF provisions in the Kyoto Protocol cannot be effectively implemented until the accounting rules have been determined. The fact that the commitments have been agreed to, but agreement on rules for meeting those commitments has not yet been negotiated, is problematic. According to researchers at the Pew Center on Global Climate Change,⁹⁸ implementation of the LULUCF provisions of the Protocol raises at least six principal issues for domestic LULUCF activities:

- What is meant by a “direct human-induced” activity?
- What is a forest and what is reforestation?
- How will uncertainty and verifiability be dealt with?
- How will accounts deal with the issues of (non) permanence and leakage?
- Which activities beyond ARD, if any, will be included, and what accounting rules should apply?
- Which carbon pools and which greenhouse gases should be considered?

Land Use Data Issues

A well-designed carbon accounting system would provide verifiable and accurate reporting of changes in carbon stocks resulting from LULUCF practices. Such data are necessary to measure compliance with commitments under the Kyoto Protocol. It should be recognized, however, that accounting for LULUCF activities under Articles 3.3 and 3.4 involves a number of uncertainties, including measurement uncertainty, uncertainty in identification of lands under Article 3.3 or 3.4, and uncertainty in determining and quantifying baselines.⁹⁹ The IPCC’s 2000 report on *Land Use, Land-Use Change, and Forestry* presents two possible accounting approaches that may be adopted for solitary or combined use in meeting these requirements: (1) the “land-based” approach and (2) the “activity-based” approach.

A “land-based” approach to accounting would consider changes in carbon stocks on lands where activities accepted under Article 3.3 or 3.4 are occurring. First, applicable activities would be defined, and lands on which the activities are occurring would be identified. Changes in global carbon stocks on such lands during a determined period of time would be calculated. Changes in carbon stocks over all land units over the specified time period would be summed for the total account of carbon dioxide emissions and removals.¹⁰⁰

An “activity-based” approach to accounting would consider the changes in carbon stocks in applicable carbon pools and/or emissions and removal of greenhouse gases resulting from LULUCF activities. Under this approach, each relevant activity’s impact on global carbon stocks would be determined per unit of area and unit of time. The activity’s impact would be multiplied by the area on which the activity occurs and by either the number of years it is applied or the number of years of the commitment period. All activities would be summed for the total account of emissions and removals.¹⁰¹

⁹⁵G. Marland and B. Schlamadinger, *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol* (Arlington, VA: Pew Center on Global Climate Change, June 2000), p. 16, web site www.pewclimate.org/projects/land_use.cfm.

⁹⁶G. Marland and B. Schlamadinger, *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol* (Arlington, VA: Pew Center on Global Climate Change, June 2000), p. 22, web site www.pewclimate.org/projects/land_use.cfm.

⁹⁷Australian Greenhouse Office, *Greenhouse Sinks and the Kyoto Protocol: An Issues Paper* (Canberra, Australia: Commonwealth of Australia, February 2000), p. 2, web site www.greenhouse.gov.au/pubs/internationalsinks/.

⁹⁸G. Marland and B. Schlamadinger, *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol* (Arlington, VA: Pew Center on Global Climate Change, June 2000), p. v, web site www.pewclimate.org/projects/land_use.cfm.

⁹⁹Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 9, web site www.ipcc.ch/pub/srlulucf-e.pdf.

¹⁰⁰Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 8, web site www.ipcc.ch/pub/srlulucf-e.pdf.

¹⁰¹Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 8, web site www.ipcc.ch/pub/srlulucf-e.pdf.

Current Global Carbon Sequestration

LULUCF is a term that refers to human activities that alter land use or affect the amount of carbon in existing forest or soil stocks. This sector involves both emissions of greenhouse gases (sources) and removal of gases from the atmosphere via carbon sequestration (sinks). Global vegetation and soils, which contain about three times as much carbon as the Earth’s atmosphere, provide an opportunity to sequester a considerable amount of carbon dioxide from the atmosphere. LULUCF practices are of particular interest to the United States, because forest land constitutes 33 percent (737 million acres) of the total U.S. land area. The United States has experienced a low rate of change in forest land area over the past 20 years, with average fluctuations of only about 0.1 percent per year since 1977. Thus, intensified management of U.S. forests has the potential to increase the growth rate and, eventually, the biomass density of the forests, thereby increasing the uptake of carbon.¹⁰² The IPCC reports that current carbon stocks are much larger in soils than in vegetation, particularly in non-forested ecosystems in middle and high latitudes (Table 33).¹⁰³

The enhancement of carbon sequestration through LULUCF activities differs from fossil fuel emission reductions in a number of ways. The potential of

LULUCF activities is limited by land availability as well as the amount of carbon that can be stored per unit of land (“saturation”). Further, carbon offsets that occur as a result of land use or forestry practices are at risk of being lost at a later time. In contrast, emission reductions from fossil fuels not burned in one year do not generally result in greater emissions in a subsequent year (“permanence”).¹⁰⁴

Accounting for the amount of carbon being sequestered annually involves a high degree of uncertainty due to lack of data and to difficulties in measuring sequestration. Further, policy or accounting uncertainties regarding which aspects of the biological carbon cycle should be included in national inventories as anthropogenic emissions and removals also abound.

The IPCC’s 2000 report on LULUCF details values for carbon sequestration as a result of LULUCF activities in a different manner. According to the IPCC, from 1850 to 1998, combined carbon dioxide emissions resulting from fossil fuel burning, industrial processes, and land-use change led to an increase in the atmospheric content of carbon dioxide of 176±10 billion metric tons carbon equivalent. Atmospheric carbon dioxide concentrations increased from approximately 285 to 366 parts per million. About 43 percent of the carbon dioxide emitted from 1850 to 1998 remains in the atmosphere. The remainder, about 230±60 billion metric tons carbon

Table 33. Global Carbon Stocks in Vegetation and Soil Carbon Pools Down to a Depth of 1 Meter
(Billion Metric Tons Carbon Equivalent)

Biome Type	Area (Billion Hectares)	Global Carbon Stocks		
		Vegetation	Soils	Total
Tropical Forests	1.76	212	216	428
Temperate Forests	1.04	59	100	159
Boreal Forests	1.37	88	471	559
Tropical Savannas	2.25	66	264	330
Temperate Grasslands	1.25	9	295	304
Deserts and Semideserts	4.55	8	191	199
Tundra	0.95	6	121	127
Wetlands	0.35	15	225	240
Croplands	1.60	3	128	131
Total	15.12	466	2,011	2,477

Note: There is considerable uncertainty in the numbers given, because of ambiguity of definitions of biomes, but the table provides an overview of the magnitude of carbon stocks in terrestrial systems.

Source: Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 4, web site www.ipcc.ch/pub/srllulucf-e.pdf.

¹⁰²U.S. Environmental Protection Agency, web site www.epa.gov/globalwarming/actions/international/landuse/index.html.
¹⁰³Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 4, web site www.ipcc.ch/pub/srllulucf-e.pdf.
¹⁰⁴G. Marland and B. Schlamadinger, *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol* (Arlington, VA: Pew Center on Global Climate Change, June 2000), p. iv, web site www.pewclimate.org/projects/land_use.cfm.

equivalent, has likely been taken up in approximately equal amounts in the oceans and in terrestrial ecosystems.¹⁰⁵

The average annual global carbon budgets for 1980-1989 and 1989-1998 are shown in Table 34. During these two decades, terrestrial ecosystems may have served as a carbon sink despite the estimate that emissions as a result of land-use change, primarily in the tropics, were 1.7 ± 0.8 billion metric tons carbon equivalent per year and 1.6 ± 0.8 billion metric tons carbon equivalent per year, respectively, during the two decades.¹⁰⁶

Estimates for Future Global Carbon Sequestration

Researchers at the Pew Center on Global Climate Change maintain that, over the next 50 years, LULUCF management practices could result in the sequestration of 60 to 87 billion metric tons carbon equivalent in the world's forests and another 23 to 44 billion metric tons carbon equivalent in the world's agricultural soils. Those estimates account for carbon that either has already been released to the atmosphere or is expected to be released. The annual carbon gain in the world's forests may reach an estimated 2.2 billion metric tons carbon equivalent by 2050.¹⁰⁷

The IPCC's 2000 report offers further estimates for future terrestrial carbon sequestration (although it should be noted that different definitions and accounting approaches under Article 3.3 of the Kyoto Protocol result in different estimates of carbon stock change).

Table 35 illustrates the estimated carbon stock changes resulting from afforestation, reforestation, and deforestation activities under the IPCC guidelines and, alternatively, under three United Nations Food and Agriculture Organization (FAO) "definitional scenarios" based on different accounting methods (assuming area conversion rates remain constant and excluding carbon in soils and wood products). The FAO scenarios include the harvest/regeneration cycle, because regeneration is defined as reforestation. Three accounting approaches are distinguished:

- In the FAO *Land-Based I Accounting Scenario*, the stock change over the full commitment period is measured, including stock losses during harvest, as well as delayed emissions from dead organic matter for reforestation. This approach results in estimated Annex I emissions of 333 to 849 million metric tons carbon equivalent per year.
- In the FAO *Land-Based II Accounting Scenario*, the carbon stock change between the beginning of the activity and the end of the commitment period is measured, including decay from harvest. This approach results in estimates for the Annex I countries that range from net sequestration of 205 million metric tons carbon equivalent per year to net emissions of 280 million metric tons carbon equivalent per year.
- In the FAO *Activity-Based Accounting Scenario*, only the accumulation of carbon in new forest stands and new dead organic matter is counted under reforestation. This approach results in estimates for the Annex I countries that range from net sequestration

Table 34. Average Annual Global Carbon Dioxide Budget, 1980-1989 and 1989-1998
(Billion Metric Tons Carbon Equivalent)

Component	1980-1989	1989-1998 ^a
(1) Emissions from Fossil Fuel Combustion and Industrial Processes . . .	5.5±0.5	6.3±0.6
(2) Storage in the Atmosphere.	3.3±0.2	3.3±0.2
(3) Ocean Uptake	2.0±0.8	2.3±0.8
(4) Net Terrestrial Uptake [(1) – (2) + (3)]	0.2±1.0	0.7±1.0
(5) Emissions From Land-Use Change	1.7±0.8	1.6±0.8 ^b
(6) Residual Terrestrial Uptake [(4) + (5)]	1.9±1.3	2.3±1.3

^aNote that there is a 1-year overlap (1989) between the two decadal time periods.

^bRepresents average annual emissions for 1989-1995, for which data are available.

Source: Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), web site www.ipcc.ch/pub/srlulucf-e.pdf.

¹⁰⁵Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 4, web site www.ipcc.ch/pub/srlulucf-e.pdf.

¹⁰⁶Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 4, web site www.ipcc.ch/pub/srlulucf-e.pdf.

¹⁰⁷G. Marland and B. Schlamadinger, *Land Use and Global Climate Change: Forests, Land Management, and the Kyoto Protocol* (Arlington, VA: Pew Center on Global Climate Change, June 2000), p. 10, web site www.pewclimate.org/projects/land_use.cfm.

of 483 million metric tons carbon equivalent per year to net emissions of 3 million metric tons carbon equivalent per year.

The IPCC definitional scenario involves transitions between forest and non-forest land uses under Article 3.3 and assumes that not only planting but also other forms of stand establishment (e.g., natural establishment) are considered to be afforestation or reforestation activities. The IPCC definitional scenario results in estimated Annex I emissions of 44 to 83 million metric tons carbon equivalent per year.¹⁰⁸

Both the FAO activity-based accounting scenario and the IPCC definitional scenario indicate that for Annex I countries, including the United States, afforestation and reforestation will function to offset a portion of carbon emissions. As shown in Table 35, however, the effects of deforestation under the FAO Activity-Based Scenario and the IPCC Definitional Accounting Scenario can greatly diminish the positive carbon sequestration effects of afforestation and reforestation activities.

In its 2000 report, the IPCC also provides estimates of carbon sequestration and avoided emissions from carbon stocks via selected Activities Implemented Jointly (AIJ) and other LULUCF projects (Table 36). A LULUCF project is defined as “a planned set of activities aimed at reducing greenhouse gas emissions or enhancing carbon stocks that is confined to one or more geographic locations in the same country and specified time period and institutional frameworks such as to allow net greenhouse gas emissions or enhancing carbon stocks to be monitored and verified.”¹⁰⁹ Currently, experience is being acquired through AIJ and other LULUCF projects that are being implemented in at least 19 countries.¹¹⁰

Included in Table 36 are 10 projects focused on decreasing emissions through avoiding deforestation and improving forest management, and 11 projects focused on increasing carbon sequestration—mostly forest projects based in tropical countries.¹¹¹ Uncertainty is involved in the assessment of these projects for a number of reasons. First, there currently exist only a limited number of projects and project types. Geographic

Table 35. Estimates of Accounted Average Annual Carbon Stock Change for Afforestation, Reforestation, and Deforestation Activities by Annex I Regions, 2008-2012
(Million Metric Tons Carbon Equivalent per Year)

Region and Activity	FAO Definitional Scenario			IPCC Definitional Scenario
	Land-Based I Accounting	Land-Based II Accounting	Activity-Based Accounting	
Annex I Boreal Region				
Afforestation/Reforestation . . .	-209 to -162	-56 to -8	5 to 48	0 to 2
Deforestation	-18	-18	-18	-18
Total	-227 to -180	-74 to -26	-13 to 30	-18 to -16
Annex I Temperate Region				
Afforestation/Reforestation . . .	-550 to -81	-134 to 303	81 to 519	7 to 44
Deforestation	-72	-72	-72	-72
Total	-622 to -153	-206 to 231	9 to 447	-65 to -28
Annex I Total				
Afforestation/Reforestation . .	-759 to -243	-190 to 295	87 to 573	7 to 46
Deforestation	-90	-90	-90	-90
Total	-849 to -333	-280 to 205	-3 to 483	-83 to -44

NA = not available.

Notes: Negative numbers indicate carbon emissions, and positive numbers indicate carbon removals. Estimated ranges include carbon in above-ground and below-ground biomass, excluding carbon in soils and in dead organic matter. Totals equal net carbon stock changes due to afforestation, reforestation, and deforestation activities, where negative numbers indicate net carbon emissions and positive numbers indicate net carbon sequestration.

Source: Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), web site www.ipcc.ch/pub/srlulucf-e.pdf.

¹⁰⁸Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 11, web site www.ipcc.ch/pub/srlulucf-e.pdf.

¹⁰⁹Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 18, web site www.ipcc.ch/pub/srlulucf-e.pdf.

¹¹⁰Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 19, web site www.ipcc.ch/pub/srlulucf-e.pdf.

¹¹¹Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 19, web site www.ipcc.ch/pub/srlulucf-e.pdf.

distribution of projects is uneven, and there have been limited field operations to date. Further, there is an absence of an internationally agreed-upon set of guidelines and methods to establish baselines and to quantify

emissions and sequestration. The projects do not report all greenhouse gas emissions or estimate leakage, and few have undergone independent review.¹¹²

Table 36. Estimates of Carbon Uptake and Carbon Emissions Avoided From Carbon Stocks, Assuming No Leakage Outside the Project Boundaries, by Selected AIJ Pilot Phase and Other LULUCF Projects, in Some Level of Implementation

Project Type (Number of Projects)	Land Area (Million Hectares)	Accumulated Carbon Uptake Over Project Lifetime (Million Metric Tons Carbon)	Estimated Carbon Uptake per Spatial Unit During Project Lifetime (Metric Tons Carbon per Hectare)	Accumulated Estimated Emissions Avoided Over Project Lifetime (Million Metric Tons Carbon)	Estimated Emissions Avoided from Carbon Stocks Over Project Lifetime (Metric Tons Carbon per Hectare)
Forest Protection (7) ^a	2.8	—	—	41 - 48	4 - 252
Improved Forest Management (3)	0.06	—	—	5.3	41 - 102
Reforestation and Afforestation (7)	0.1	10 - 10.4	26 - 328	—	—
Agroforestry (2)	0.2	10.5 - 10.8	26 - 56	—	—
Multi-Component and Community Forest (2) . .	0.35	9.7	0.2 - 129	—	—

^aProtecting an existing forest does not necessarily ensure a long-term contribution to the mitigation of the greenhouse effect because of the potential for leakage and reversibility through human activities, disturbances, or environmental change. This table does not provide an assessment in relation to these issues. Sound project design and management, accounting, and monitoring would be required to address these issues.

AIJ = Activities Implemented Jointly. LULUCF = Land Use, Land-Use Change, and Forestry.

Notes: Projects included are those for which sufficient data are available. Soil carbon management, bioenergy, and other projects are excluded for this reason. "Some level of implementation" includes projects that have been partially funded and have begun activities on the ground that will generate increases in carbon stocks and reductions in greenhouse gas emissions. "Other LULUCF projects" refers to selected non-AIJ projects and projects with Annex I countries. Estimated changes in carbon stocks generally have been reported by project developers, do not use standardized methods, and may not be comparable; only some have been independently reviewed. Non-CO₂ greenhouse gas emissions are not reported.

Source: Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), web site www.ipcc.ch/pub/srlulucf-e.pdf.

¹¹²Intergovernmental Panel on Climate Change, *Summary for Policymakers: Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, May 2000), p. 19, web site www.ipcc.ch/pub/srlulucf-e.pdf.

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Glossary

Acid stabilization: A circumstance where the pH of the waste mixture in an animal manure management system is maintained near 7.0, optimal conditions for methane production.

Aerobic bacteria: Microorganisms living, active, or occurring only in the presence of oxygen.

Aerobic decomposition: The breakdown of a molecule into simpler molecules or atoms by microorganisms under favorable conditions of oxygenation.

Aerosols: Airborne particles.

Afforestation: Planting of new forests on lands that have not been recently forested.

Agglomeration: The clustering of disparate elements.

Airshed: An area or region defined by settlement patterns or geology that results in discrete atmospheric conditions.

Albedo: The fraction of incident light or electromagnetic radiation that is reflected by a surface or body. See *Planetary albedo*.

Anaerobes: Organisms that live and are active only in the absence of oxygen.

Anaerobic bacteria: Microorganisms living, active, or occurring only in the absence of oxygen.

Anaerobic decomposition: The breakdown of molecules into simpler molecules or atoms by microorganisms that can survive in the partial or complete absence of oxygen.

Anaerobic lagoon: A liquid-based manure management system, characterized by waste residing in water to a depth of at least six feet for a period ranging between 30 and 200 days.

Anode: A positive electrode, as in a battery, radio tube, etc.

Anthracite: The highest rank of coal; used primarily for residential and commercial space heating. It is a hard, brittle, and black lustrous coal, often referred to as hard coal, containing a high percentage of fixed carbon and a low percentage of volatile matter. The moisture content of fresh-mined anthracite generally is less than 15 percent. The heat content of anthracite ranges from 22 to 28

million Btu per ton on a moist, mineral-matter-free basis. The heat content of anthracite coal consumed in the United States averages 25 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter). Note: Since the 1980's, anthracite refuse or mine waste has been used for steam electric power generation. This fuel typically has a heat content of 15 million Btu per ton or less.

Anthropogenic: Made or generated by a human or caused by human activity. The term is used in the context of global climate change to refer to gaseous emissions that are the result of human activities, as well as other potentially climate-altering activities, such as deforestation.

API Gravity: A scale expressing the density of petroleum products as established by the American Petroleum Institute.

Asphalt: A dark-brown to black cement-like material obtained by petroleum processing, containing bitumens as the predominant constituents. Includes crude asphalt as well as the following finished products: cements, the asphalt content of emulsions (exclusive of water), and petroleum distillates blended with asphalt to make cut-back asphalts.

Associated gas: Natural gas found mixed with crude oil in underground reservoirs, released as a byproduct of oil production.

Aviation gasoline (finished): A complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in aviation reciprocating engines. Fuel specifications are provided in ASTM Specification D 910 and Military Specification MIL-G-5572. Note: Data on blending components are not counted in data on finished aviation gasoline.

Balancing item: A measurement of the difference between the reported amount of natural gas produced and the reported amount consumed.

Biofuels: Organic materials, such as wood, waste, and alcohol fuels, burned for energy purposes.

Biogas: The gas produced from the anaerobic decomposition of organic material in a landfill.

Biogenic: Produced by the actions of living organisms.

Biomass: Materials that are biological in origin, including organic material (both living and dead) from above and below ground, for example, trees, crops, grasses, tree litter, roots, and animals and animal waste.

Biosphere: The portion of the Earth and its atmosphere that can support life. The part of the global carbon cycle that includes living organisms and biogenic organic matter.

Bituminous coal: A dense coal, usually black, sometimes dark brown, often with well-defined bands of bright and dull material, used primarily as fuel in steam-electric power generation, with substantial quantities also used for heat and power applications in manufacturing and to make coke. Bituminous coal is the most abundant coal in active U.S. mining regions. Its moisture content usually is less than 20 percent. The heat content of bituminous coal ranges from 21 to 30 million Btu per ton on a moist, mineral-matter-free basis. The heat content of bituminous coal consumed in the United States averages 24 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

BOD₅: The biochemical oxygen demand of wastewater during decomposition occurring over a 5-day period. A measure of the organic content of wastewater.

Bromofluorocarbons (halons): Inert, nontoxic chemicals that have at least one bromine atom in their chemical makeup. They evaporate without leaving a residue and are used in fire extinguishing systems, especially for large computer installations.

Bunker fuel: Fuel supplied to ships and aircraft, both domestic and foreign, consisting primarily of residual and distillate fuel oil for ships and kerosene-based jet fuel for aircraft. The term “international bunker fuels” is used to denote the consumption of fuel for international transport activities. *Note:* For the purposes of greenhouse gas emissions inventories, data on emissions from combustion of international bunker fuels are subtracted from national emissions totals. Historically, bunker fuels have meant only ship fuel. See *Vessel bunkering*.

Calcination: A process in which a material is heated to a high temperature without fusing, so that hydrates, carbonates, or other compounds are decomposed and the volatile material is expelled.

Calcium sulfate: A white crystalline salt, insoluble in water. Used in Keene’s cement, in pigments, as a paper filler, and as a drying agent.

Calcium sulfite: A white powder, soluble in dilute sulfuric acid. Used in the sulfite process for the manufacture of wood pulp.

Capital stock: Property, plant and equipment used in the production, processing and distribution of energy resources.

Carbon black: An amorphous form of carbon, produced commercially by thermal or oxidative decomposition of hydrocarbons and used principally in rubber goods, pigments, and printer’s ink.

Carbon budget: Carbon budget: The balance of the exchanges (incomes and losses) of carbon between carbon sinks (e.g., atmosphere and biosphere) in the carbon cycle. See *Carbon cycle* and *Carbon sink*.

Carbon cycle: All carbon sinks and exchanges of carbon from one sink to another by various chemical, physical, geological, and biological processes. See *Carbon sink* and *Carbon budget*.

Carbon dioxide (CO₂): A colorless, odorless, non-poisonous gas that is a normal part of Earth’s atmosphere. Carbon dioxide is a product of fossil-fuel combustion as well as other processes. It is considered a greenhouse gas as it traps heat (infrared energy) radiated by the Earth into the atmosphere and thereby contributes to the potential for global warming. Other greenhouse gases are measured in relation to the global warming potential (GWP) of carbon dioxide, which by international scientific convention is assigned a value of one (1). See *Global warming potential (GWP)* and *Greenhouse gases*.

Carbon dioxide equivalent: The amount of carbon dioxide by weight emitted into the atmosphere that would produce the same estimated radiative forcing as a given weight of another radiatively active gas. Carbon dioxide equivalents are computed by multiplying the weight of the gas being measured (for example, methane) by its estimated global warming potential (which is 21 for methane). “Carbon equivalent units” are defined as carbon dioxide equivalents multiplied by the carbon content of carbon dioxide (i.e., 12/44).

Carbon flux: See *Carbon budget*.

Carbon intensity: The amount of carbon by weight emitted per unit of energy consumed. A common measure of carbon intensity is weight of carbon per British thermal unit (Btu) of energy. When there is only one fossil fuel under consideration, the carbon intensity and the emissions coefficient are the same thing. When there are several fuels, carbon intensity is based on their combined emissions coefficients weighted by their energy consumption levels. See *Emissions coefficient* and *Carbon output rate*.

Carbon output rate: The amount of carbon by weight per kilowatthour of electricity produced.

Carbon sequestration: The fixation of atmospheric carbon dioxide in a carbon sink through biological or physical processes.

Carbon sink: A reservoir that absorbs or takes up released carbon from another part of the carbon cycle. The four sinks, which are regions of the Earth within which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually including freshwater systems), oceans, and sediments (including fossil fuels).

Catalytic converter: A device containing a catalyst for converting automobile exhaust into mostly harmless products.

Cesspool: An underground reservoir for liquid waste, typically household sewage.

Chlorofluorocarbons (CFCs): A family of inert, non-toxic, easily liquefied chemicals used in refrigeration, air conditioning, packaging, and insulation, or as solvents or aerosol propellants.

Clean Development Mechanism (CDM): A Kyoto Protocol program that enables industrialized countries to finance emissions-avoiding projects in developing countries and receive credit for reductions achieved against their own emissions limitation targets. See *Kyoto Protocol*.

Climate: The average course or condition of the weather over a period of years as exhibited by temperature, humidity, wind velocity, and precipitation.

Climate change: A term used to refer to all forms of climatic inconsistency, but especially to significant change from one prevailing climatic condition to another. In some cases, "climate change" has been used synonymously with the term "global warming"; scientists, however, tend to use the term in a wider sense inclusive of natural changes in climate as well as climatic cooling.

Clinker: Powdered cement, produced by heating a properly proportioned mixture of finely ground raw materials (calcium carbonate, silica, alumina, and iron oxide) in a kiln to a temperature of about 2,700°F.

Cloud condensation nuclei: Aerosol particles that provide a platform for the condensation of water vapor, resulting in clouds with higher droplet concentrations and increased albedo.

Coal coke: See *Coke (coal)*.

Coalbed methane: Methane produced from coalbeds in the same way that natural gas is produced from other strata. See "methane."

Coke (coal): A solid carbonaceous residue derived from low-ash, low-sulfur bituminous coal from which the volatile constituents are driven off by baking in an oven at temperatures as high as 2,000 degrees Fahrenheit so that the fixed carbon and residual ash are fused together. Coke is used as a fuel and as a reducing agent in smelting iron ore in a blast furnace. Coke from coal is grey, hard, and porous and has a heating value of 24.8 million Btu per ton.

Coke (petroleum): A residue high in carbon content and low in hydrogen that is the final product of thermal decomposition in the condensation process in cracking. This product is reported as marketable coke or catalyst coke. The conversion is 5 barrels (of 42 U.S. gallons each) per short ton. Coke from petroleum has a heating value of 6.024 million Btu per barrel.

Combustion: Chemical oxidation accompanied by the generation of light and heat.

Combustion chamber: An enclosed vessel in which chemical oxidation of fuel occurs.

Conference of the Parties (COP): The collection of nations that have ratified the Framework Convention on Climate Change (FCCC). The primary role of the COP is to keep implementation of the FCCC under review and make the decisions necessary for its effective implementation. See *Framework Convention on Climate Change (FCCC)*.

Cracking: The refining process of breaking down the larger, heavier, and more complex hydrocarbon molecules into simpler and lighter molecules.

Criteria pollutant: A pollutant determined to be hazardous to human health and regulated under EPA's National Ambient Air Quality Standards. The 1970 amendments to the Clean Air Act require EPA to describe the health and welfare impacts of a pollutant as the "criteria" for inclusion in the regulatory regime.

Crop residue: Organic residue remaining after the harvesting and processing of a crop.

Cultivar: A horticulturally or agriculturally derived variety of a plant.

Deforestation: The net removal of trees from forested land.

Degasification system: The methods employed for removing methane from a coal seam that could not otherwise be removed by standard ventilation fans and thus would pose a substantial hazard to coal miners. These systems may be used prior to mining or during mining activities.

Degradable organic carbon: The portion of organic carbon present in such solid waste as paper, food waste, and yard waste that is susceptible to biochemical decomposition.

Desulfurization: The removal of sulfur, as from molten metals, petroleum oil, or flue gases.

Diffusive transport: The process by which particles of liquids or gases move from an area of higher concentration to an area of lower concentration.

Distillate fuel: A general classification for one of the petroleum fractions produced in conventional distillation operations. It includes diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. Products known as No. 1, No. 2, and No. 4 fuel oils are used primarily for space heating and electric power generation.

Efflux: An outward flow.

Electrical generating capacity: The full-load continuous power rating of electrical generating facilities, generators, prime movers, or other electric equipment (individually or collectively).

EMCON Methane Generation Model: A model for estimating the production of methane from municipal solid waste landfills.

Emissions: Anthropogenic releases of gases to the atmosphere. In the context of global climate change, they consist of radiatively important greenhouse gases (e.g., the release of carbon dioxide during fuel combustion).

Emissions coefficient: A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., pounds of carbon dioxide emitted per Btu of fossil fuel consumed).

Enteric fermentation: A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

Eruption: An act or instance of belching.

Ethyl tertiary butyl ether (ETBE): A colorless, flammable, oxygenated hydrocarbon blend stock.

Ethylene: An olefinic hydrocarbon recovered from refinery or petrochemical processes.

Ethylene dichloride: A colorless, oily liquid used as a solvent and fumigant for organic synthesis, and for ore flotation.

Facultative bacteria: Bacteria that grow equally well under aerobic and anaerobic conditions.

Flange: A rib or a rim for strength, for guiding, or for attachment to another object (e.g., on a pipe).

Flared natural gas: Natural gas burned in flares on the well site or at gas processing plants.

Flatus: Gas generated in the intestines or the stomach of an animal.

Flue gas desulfurization: Equipment used to remove sulfur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Also referred to as scrubbers. Chemicals such as lime are used as scrubbing media.

Fluidized-bed combustion: A method of burning particulate fuel, such as coal, in which the amount of air required for combustion far exceeds that found in conventional burners. The fuel particles are continually fed into a bed of mineral ash in the proportions of 1 part fuel to 200 parts ash, while a flow of air passes up through the bed, causing it to act like a turbulent fluid.

Flux material: A substance used to promote fusion, e.g., of metals or minerals.

Fodder: Coarse food for domestic livestock.

Forestomach: See *Rumen*.

Fossil fuel: Any naturally occurring organic fuel formed in the earth's crust, such as petroleum, coal, or natural gas.

Framework Convention on Climate Change (FCCC): An agreement opened for signature at the "Earth Summit" in Rio de Janeiro, Brazil, on June 4, 1992, which has the goal of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent significant anthropogenically forced climate change. See *Climate change*.

Fuel cycle: The entire set of sequential processes or stages involved in the utilization of fuel, including extraction, transformation, transportation, and combustion. Emissions generally occur at each stage of the fuel cycle.

Fugitive emissions: Unintended leaks of gas from the processing, transmission, and/or transportation of fossil fuels.

Gasification: A method for exploiting poor-quality coal and thin coal seams by burning the coal in place to produce combustible gas that can be collected and burned to generate power or processed into chemicals and fuels.

Gate station: Location where the pressure of natural gas being transferred from the transmission system to the distribution system is lowered for transport through small diameter, low pressure pipelines.

Geothermal: Pertaining to heat within the Earth.

Global climate change: See *Climate change*.

Global warming: An increase in the near surface temperature of the Earth. Global warming has occurred in the distant past as the result of natural influences, but the term is today most often used to refer to the warming predicted to occur as a result of increased anthropogenic emissions of greenhouse gases. See *Climate change*.

Global warming potential (GWP): An index used to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emission of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a fixed period of time, such as 100 years.

Greenhouse effect: The result of water vapor, carbon dioxide, and other gases trapping radiant (infrared) energy, thereby keeping the earth's surface warmer than it would otherwise be. Greenhouse gases within the lower levels of the atmosphere trap this radiation, which would otherwise escape into space, and subsequent re-radiation of some of this energy back to the Earth maintains higher surface temperatures than would occur if the gases were absent. See *Greenhouse gases*.

Greenhouse gases: Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave radiation, thus preventing long-wave radiant energy from leaving the atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.

Gross gas withdrawal: The full-volume of compounds extracted at the wellhead, including nonhydrocarbon gases and natural gas plant liquids.

Gypsum: The most common sulfate mineral. Used in wallboard.

Halogenated substances: A volatile compound containing halogens, such as chlorine, fluorine or bromine.

Halons: See *Bromofluorocarbons*.

Heating degree-day: The number of degrees per day that the average daily temperature is below 65 degrees Fahrenheit.

Herbivore: A plant-eating animal.

Hydrocarbon: An organic chemical compound of hydrogen and carbon in either gaseous, liquid, or solid phase. The molecular structure of hydrocarbon compounds varies from the simple (e.g., methane, a constituent of natural gas) to the very heavy and very complex.

Hydrochlorofluorocarbons (HCFCs): Chemicals composed of one or more carbon atoms and varying numbers of hydrogen, chlorine, and fluorine atoms.

Hydrofluorocarbons (HFCs): A group of man-made chemicals composed of one or two carbon atoms and varying numbers of hydrogen and fluorine atoms. Most HFCs have 100-year Global Warming Potentials in the thousands.

Hydroxyl radical (OH): An important chemical scavenger of many trace gases in the atmosphere that are greenhouse gases. Atmospheric concentrations of OH affect the atmospheric lifetimes of greenhouse gases, their abundance, and, ultimately, the effect they have on climate.

Intergovernmental Panel on Climate Change (IPCC): A panel established jointly in 1988 by the World Meteorological Organization and the United Nations Environment Program to assess the scientific information relating to climate change and to formulate realistic response strategies.

International bunker fuels: See *Bunker fuels*.

Jet fuel: See *Kerosene-type jet fuel* and *Naphtha-type jet fuel*.

Joint Implementation (JI): Agreements made between two or more nations under the auspices of the Framework Convention on Climate Change (FCCC) whereby a developed country can receive "emissions reduction units" when it helps to finance projects that reduce net emissions in another developed country (including countries with economies in transition).

Kerosene: A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps. Kerosene has a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent recovery point, a final boiling point of 572 degrees Fahrenheit, and a minimum flash point of 100 degrees Fahrenheit. Included are No. 1-K and No. 2-K, the two grades recognized by ASTM Specification D 3699 as well as all other grades of kerosene called range or stove oil, which have properties similar to those of No. 1 fuel oil. See *Kerosene-type jet fuel*.

Kerosene-type jet fuel: A kerosene-based product having a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent recovery point and a final maximum boiling point of 572 degrees Fahrenheit and meeting ASTM Specification D 1655 and Military Specifications MIL-T-5624P and MIL-T-83133D (Grades JP-5 and JP-8). It is used for commercial and military turbojet and turboprop aircraft engines.

Kyoto Protocol: The result of negotiations at the third Conference of the Parties (COP-3) in Kyoto, Japan, in December of 1997. The Kyoto Protocol sets binding greenhouse gas emissions targets for countries that sign and ratify the agreement. The gases covered under the Protocol include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride.

Ketone-alcohol (cyclohexanol): An oily, colorless, hygroscopic liquid with a camphor-like odor. Used in soapmaking, dry cleaning, plasticizers, insecticides, and germicides.

Leachate: A liquid produced as water percolates through wastes, collecting contaminants.

Lignite: The lowest rank of coal, often referred to as brown coal, used almost exclusively as fuel for steam-electric power generation. It is brownish-black and has a high inherent moisture content, sometimes as high as 45 percent. The heat content of lignite ranges from 9 to 17 million Btu per ton on a moist, mineral-matter-free basis. The heat content of lignite consumed in the United States averages 13 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

Liquefied petroleum gases (LPG): Ethane, ethylene, propane, propylene, normal butane, butylene, and isobutane produced at refineries or natural gas processing plants, including plants that fractionate new natural gas plant liquids.

Lubricant: A substance used to reduce friction between bearing surfaces or as a process material, either incorporated into other materials used as aids in manufacturing processes or as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Other substances may be added to impart or improve useful properties. Does not include byproducts of lubricating oil from solvent extraction or tars derived from de-asphalting. Lubricants include all grades of lubricating oils from spindle oil to cylinder oil and those used in greases. Lubricant categories are paraffinic and naphthenic.

Methane (CH₄): A hydrocarbon gas that is the principal constituent of natural gas. Methane has a 100-year Global Warming Potential of 21.

Methanogens: Bacteria that synthesize methane, requiring completely anaerobic conditions for growth.

Methanol: A light alcohol that can be used for gasoline blending. See oxygenate.

Methanotrophs: Bacteria that use methane as food and oxidize it into carbon dioxide.

Methyl chloroform (trichloroethane): An industrial chemical (CH₃CCl₃) used as a solvent, aerosol propellant, and pesticide and for metal degreasing.

Methyl tertiary butyl ether (MTBE): A colorless, flammable, liquid oxygenated hydrocarbon containing 18.15 percent oxygen.

Methylene chloride: A colorless liquid, nonexplosive and practically nonflammable. Used as a refrigerant in centrifugal compressors, a solvent for organic materials, and a component in nonflammable paint removers.

Mole: The quantity of a compound or element that has a weight in grams numerically equal to its molecular weight. Also referred to as gram molecule or gram molecular weight.

Montreal Protocol: The Montreal Protocol on Substances that Deplete the Ozone Layer (1987). An international agreement, signed by most of the industrialized nations, to substantially reduce the use of chlorofluorocarbons (CFCs). Signed in January 1989, the original document called for a 50-percent reduction in CFC use by 1992 relative to 1986 levels. The subsequent London Agreement called for a complete elimination of CFC use by 2000. The Copenhagen Agreement, which called for a complete phaseout by January 1, 1996, was implemented by the U.S. Environmental Protection Agency.

Motor gasoline (finished): A complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines. Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 to 158 degrees Fahrenheit at the 10 percent recovery point to 365 to 374 degrees Fahrenheit at the 90 percent recovery point. "Motor Gasoline" includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline, but excludes aviation gasoline. Note: Volumetric data on blending components, such as oxygenates, are not counted in data on finished motor gasoline until the blending components are blended into the gasoline.

Multiple cropping: A system of growing several crops on the same field in one year.

Municipal solid waste: Residential solid waste and some nonhazardous commercial, institutional, and industrial wastes.

Naphtha: A generic term applied to a petroleum fraction with an approximate boiling range between 122 and 400°F.

Naphtha-type jet fuel: A fuel in the heavy naphtha boiling range having an average gravity of 52.8 degrees API, 20 to 90 percent distillation temperatures of 290 degrees to 470 degrees Fahrenheit, and meeting Military Specification MIL-T-5624L (Grade JP-4). It is used primarily for military turbojet and turboprop aircraft engines because it has a lower freeze point than other aviation fuels and meets engine requirements at high altitudes and speeds.

Natural gas: A mixture of hydrocarbons and small quantities of various nonhydrocarbons in the gaseous phase or in solution with crude oil in natural underground reservoirs.

Natural gas liquids (NGLs): Those hydrocarbons in natural gas that are separated as liquids from the gas. Includes natural gas plant liquids and lease condensate.

Natural gas, pipeline quality: A mixture of hydrocarbon compounds existing in the gaseous phase with sufficient energy content, generally above 900 Btu, and a small enough share of impurities for transport through commercial gas pipelines and sale to end-users.

Nitrogen oxides (NO_x): Compounds of nitrogen and oxygen produced by the burning of fossil fuels.

Nitrous oxide (N₂O): A colorless gas, naturally occurring in the atmosphere. Nitrous oxide has a 100-year Global Warming Potential of 310.

Nonmethane volatile organic compounds (NMVOCs): Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

Octane: A flammable liquid hydrocarbon found in petroleum. Used as a standard to measure the anti-knock properties of motor fuel.

Oil reservoir: An underground pool of liquid consisting of hydrocarbons, sulfur, oxygen, and nitrogen trapped within a geological formation and protected from evaporation by the overlying mineral strata.

Organic content: The share of a substance that is of animal or plant origin.

Organic waste: Waste material of animal or plant origin.

Oxidize: To chemically transform a substance by combining it with oxygen.

Oxygenates: Substances which, when added to gasoline, increase the amount of oxygen in that gasoline blend. Ethanol, Methyl Tertiary Butyl Ether (MTBE), Ethyl Tertiary Butyl Ether (ETBE), and methanol are common oxygenates.

Ozone: A molecule made up of three atoms of oxygen. Occurs naturally in the stratosphere and provides a protective layer shielding the Earth from harmful ultraviolet radiation. In the troposphere, it is a chemical oxidant, a greenhouse gas, and a major component of photochemical smog.

Ozone precursors: Chemical compounds, such as carbon monoxide, methane, nonmethane hydrocarbons, and nitrogen oxides, which in the presence of solar radiation react with other chemical compounds to form ozone.

Paraffinic hydrocarbons: Straight-chain hydrocarbon compounds with the general formula C_nH_{2n+2}.

Perfluorocarbons (PFCs): A group of man-made chemicals composed of one or two carbon atoms and four to six fluorine atoms, containing no chlorine. PFCs have no commercial uses and are emitted as a byproduct of aluminum smelting and semiconductor manufacturing. PFCs have very high 100-year Global Warming Potentials and are very long-lived in the atmosphere.

Perfluoromethane: A compound (CF₄) emitted as a byproduct of aluminum smelting.

Petrochemical feedstock: Feedstock derived from petroleum, used principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics. The categories reported are naphthas (endpoint less than 401°F) and other oils (endpoint equal to or greater than 401°F).

Petroleum: Hydrocarbon mixtures, including crude oil, lease condensate, natural gas, products of natural gas processing plants, refined products, semifinished products, and blending materials.

Petroleum coke: See *Coke (petroleum)*.

Photosynthesis: The manufacture by plants of carbohydrates and oxygen from carbon dioxide and water in the presence of chlorophyll, with sunlight as the energy source. Carbon is sequestered and oxygen and water vapor are released in the process.

Pig iron: Crude, high-carbon iron produced by reduction of iron ore in a blast furnace.

Pipeline, distribution: A pipeline that conveys gas from a transmission pipeline to its ultimate consumer.

Pipeline, gathering: A pipeline that conveys gas from a production well/field to a gas processing plant or transmission pipeline for eventual delivery to end-use consumers.

Pipeline, transmission: A pipeline that conveys gas from a region where it is produced to a region where it is to be distributed.

Planetary albedo: The fraction of incident solar radiation that is reflected by the Earth-atmosphere system and returned to space, mostly by backscatter from clouds in the atmosphere.

Pneumatic device: A device moved or worked by air pressure.

Polystyrene: A polymer of styrene that is a rigid, transparent thermoplastic with good physical and electrical insulating properties, used in molded products, foams, and sheet materials.

Polyvinyl chloride (PVC): A polymer of vinyl chloride. Tasteless, odorless, insoluble in most organic solvents. A member of the family vinyl resin, used in soft flexible films for food packaging and in molded rigid products, such as pipes, fibers, upholstery, and bristles.

Post-mining emissions: Emissions of methane from coal occurring after the coal has been mined, during transport or pulverization.

Radiative forcing: A change in average net radiation at the top of the troposphere (known as the tropopause) because of a change in either incoming solar or exiting infrared radiation. A positive radiative forcing tends on average to warm the earth's surface; a negative radiative forcing on average tends to cool the earth's surface. Greenhouse gases, when emitted into the atmosphere, trap infrared energy radiated from the earth's surface and therefore tend to produce positive radiative forcing. See *Greenhouse gases*.

Radiatively active gases: Gases that absorb incoming solar radiation or outgoing infrared radiation, affecting the vertical temperature profile of the atmosphere. See *Radiative forcing*.

Ratoon crop: A crop cultivated from the shoots of a perennial plant.

Redox potential: A measurement of the state of oxidation of a system.

Reflectivity: The ratio of the energy carried by a wave after reflection from a surface to its energy before reflection.

Reforestation: Replanting of forests on lands that have recently been harvested or otherwise cleared of trees.

Reformulated gasoline: Finished motor gasoline formulated for use in motor vehicles, the composition and properties of which meet the requirements of the reformulated gasoline regulations promulgated by the U.S. Environmental Protection Agency under Section 211(k) of the Clean Air Act. Note: This category includes oxygenated fuels program reformulated gasoline (OPRG) but excludes reformulated gasoline blendstock for oxygenate blending (RBOB).

Renewable energy: Energy obtained from sources that are essentially inexhaustible (unlike, for example, the fossil fuels, of which there is a finite supply). Renewable sources of energy include wood, waste, geothermal, wind, photovoltaic, and solar thermal energy.

Residual fuel oil: The heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. It conforms to ASTM Specifications D 396 and D 975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO Symbol F-770). It is used in steam-powered vessels in government service and inshore powerplants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

Rumen: The large first compartment of the stomach of certain animals in which cellulose is broken down by the action of bacteria.

Sample: A set of measurements or outcomes selected from a given population.

Sequestration: See *Carbon sequestration*.

Septic tank: A tank in which the solid matter of continuously flowing sewage is disintegrated by bacteria.

Sinter: A chemical sedimentary rock deposited by precipitation from mineral waters, especially siliceous sinter and calcareous sinter.

Sodium silicate: A grey-white powder soluble in alkali and water, insoluble in alcohol and acid. Used to fire-proof textiles, in petroleum refining and corrugated paperboard manufacture, and as an egg preservative. Also referred to as liquid glass, silicate of soda, sodium metasilicate, soluble glass, and water glass.

Sodium tripolyphosphate: A white powder used for water softening and as a food additive and texturizer.

Stabilization lagoon: A shallow artificial pond used for the treatment of wastewater. Treatment includes removal of solid material through sedimentation, the decomposition of organic material by bacteria, and the removal of nutrients by algae.

Still gas: Any form or mixture of gases produced in refineries by distillation, cracking, reforming, and other processes. Principal constituents are methane, ethane, ethylene, normal butane, butylene, propane, propylene, etc. Used as a refinery fuel and as a petrochemical feedstock.

Stratosphere: The region of the upper atmosphere extending from the tropopause (8 to 15 kilometers altitude) to about 50 kilometers. Its thermal structure, which is determined by its radiation balance, is generally very stable with low humidity.

Stripper well: A well that produces 60 million cubic feet of gas per day or less for a period of three consecutive months while producing at its maximum flow rate.

Styrene: A colorless, toxic liquid with a strong aromatic aroma. Insoluble in water, soluble in alcohol and ether; polymerizes rapidly; can become explosive. Used to make polymers and copolymers, polystyrene plastics, and rubber.

Subbituminous coal: A coal whose properties range from those of lignite to those of bituminous coal and used primarily as fuel for steam-electric power generation. It may be dull, dark brown to black, soft and crumbly, at the lower end of the range, to bright, jet black, hard, and relatively strong, at the upper end. Subbituminous coal contains 20 to 30 percent inherent moisture by weight. The heat content of subbituminous coal ranges from 17 to 24 million Btu per ton on a moist, mineral-matter-free basis. The heat content of subbituminous coal consumed in the United States averages 17 to 18 million Btu per ton, on the as-received basis (i.e., containing both inherent moisture and mineral matter).

Sulfur dioxide (SO₂): A toxic, irritating, colorless gas soluble in water, alcohol, and ether. Used as a chemical intermediate, in paper pulping and ore refining, and as a solvent.

Sulfur hexafluoride (SF₆): A colorless gas soluble in alcohol and ether, and slightly less soluble in water. It is used as a dielectric in electronics. It possesses the highest 100-year Global Warming Potential of any gas (23,900).

Sulfur oxides (SO_x): Compounds containing sulfur and oxygen, such as sulfur dioxide (SO₂) and sulfur trioxide (SO₃).

Tertiary amyl methyl ether (TAME): An oxygenate blend stock formed by the catalytic etherification of isoamylene with methanol.

Troposphere: The inner layer of the atmosphere below about 15 kilometers, within which there is normally a steady decrease of temperature with increasing altitude. Nearly all clouds form and weather conditions manifest themselves within this region. Its thermal structure is caused primarily by the heating of the earth's surface by solar radiation, followed by heat transfer through turbulent mixing and convection.

Uncertainty: A measure used to quantify the plausible maximum and minimum values for emissions from any source, given the biases inherent in the methods used to calculate a point estimate and known sources of error.

Vapor displacement: The release of vapors that had previously occupied space above liquid fuels stored in tanks. These releases occur when tanks are emptied and filled.

Ventilation system: A method for reducing methane concentrations in coal mines to non-explosive levels by blowing air across the mine face and using large exhaust fans to remove methane while mining operations proceed.

Vessel bunkering: Includes sales for the fueling of commercial or private boats, such as pleasure craft, fishing boats, tugboats, and ocean-going vessels, including vessels operated by oil companies. Excluded are volumes sold to the U.S. Armed Forces.

Volatile organic compounds (VOCs): Organic compounds that participate in atmospheric photochemical reactions.

Volatile solids: A solid material that is readily decomposable at relatively low temperatures.

Waste flow: Quantity of a waste stream generated by an activity.

Wastewater: Water that has been used and contains dissolved or suspended waste materials.

Wastewater, domestic and commercial: Wastewater (sewage) produced by domestic and commercial establishments.

Wastewater, industrial: Wastewater produced by industrial processes.

Water vapor: Water in a vaporous form, especially when below boiling temperature and diffused (e.g., in the atmosphere).

Waxes: Solid or semisolid materials derived from petroleum distillates or residues. Light-colored, more or less translucent crystalline masses, slightly greasy to the touch, consisting of a mixture of solid hydrocarbons in which the paraffin series predominates. Included are all marketable waxes, whether crude scale or fully refined. Used primarily as industrial coating for surface protection.

Weanling system: A cattle management system that places calves on feed starting at 165 days of age and continues until the animals have reached slaughter weight.

Wellhead: The top of, or a structure built over, a well.

Wetlands: Areas regularly saturated by surface or groundwater and subsequently characterized by a prevalence of vegetation adapted for life in saturated-soil conditions.

Wood energy: Wood and wood products used as fuel, including roundwood (cordwood), limbwood, wood chips, bark, sawdust, forest residues, and charcoal.

Yearling system: A cattle management system that includes a stocker period from 165 days of age to 425 days of age followed by a 140-day feedlot period.